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NUREG-1147
Rev. 1

ORIGINAL

Seismic Safety Research Program Plan

U.S. Nuclear Regulatory Commission

Office of Nuclear Regulatory Research

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Seismic Safety Research Program Plan

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Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
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U.S. Nuclear Regulatory Commission

Previous Reports in Series

NUREG-1147, "Seismic Safety Research Program Plan,"

Office of Nuclear Regulatory Research, Published June 1985

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ABSTRACT

This document presents a plan for seismic research to be performed by the Structural and Seismic Engineering Branch in the Office of Nuclear Regulatory Research. The plan describes the regulatory needs and related research necessary to address the following issues: uncertainties in seismic hazard, earthquakes larger than the design basis, seismic vulnerabilities, shifts in building frequency, piping design, and the adequacy of current criteria and methods. In addition to presenting current and proposed research within the NRC, the plan discusses research sponsored by other domestic and foreign sources.

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FOREWORD

This document presents a plan for seismic research to be performed by the Structural and Seismic Engineering Branch, Division of Engineering, in the Office of Nuclear Regulatory Research. This plan describes the safety issues, regulatory needs, and the research necessary to address these needs. The plan also discusses the relationship between current and proposed research within the NRC and research sponsored by other government agencies, universities, industry groups, professional societies, and foreign sources.

This plan is a living document, and it is expected that it will be revised periodically to take into account new issues and needs, our experience in implementing the plan, and comments received from interested parties within the NRC and among the public.

Comments on this document are welcome at any time and will be considered in the development of subsequent revisions to this plan. They need not be restricted to the research activities described herein; comments identifying omissions or recommending additional research are also welcome. Comments should be addressed to:

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1. INTRODUCTION

Earthquakes are among the most severe of the natural hazards faced by nuclear power plants since very large earthquakes can jeopardize design concepts of redundancy and defense-in-depth through common mode failure (Refs. 1 through 7). The Seismic Safety Research Program Plan describes NRC research activities to (1) improve estimates of earthquake hazards by identifying potential earthquake sources and determining the propagation of seismic energy with distance and (2) assess the effects of earthquakes on nuclear power plants by determining the capability of structures, systems, and components to withstand earthquakes larger than their design basis. New seismological considerations that may require the reevaluation of plants for earthquakes larger than their original design bases include the discovery of the Hosgri fault off California near the Diablo Canyon plants; the 1886 Charleston, South Carolina, earthquake, which may be considered to occur in a wider area then originally thought, or the 1982 New Brunswick, Canada, earthquake, which could represent the largest historical earthquake in the tectonic province, including much of New England and southern New York.

The plan addresses short-term, high-priority research to support immediate needs relative to quantifying and reducing uncertainty associated with current regulatory requirements and long-term research to resolve concerns related to seismic design margins. Short-term research improves requirements by removing conservatisms where they are unnecessary and adding conservatisms where weaknesses in the regulations exist, thereby achieving a more balanced design. Long-term research, on the other hand, aims at more strategic questions involving the overall view as to how important earthquakes are in the regulatory process. NRC's seismic research has been divided into the broad general categories of earth sciences, seismic margins, fragilities and response, and validation. Research associated with these four program areas can be summarized as:

Earth Sciences - Research designed to address issues that contribute to the uncertainty in seismic hazard assessment, especially for nuclear facilities located in the Eastern and Central United States. These issues are uncertainty in establishing seismic source zones, uncertainty in the propagation of seismic energy, and uncertainty in the site-specific ground motion response, including soil failure. The earth sciences research program consists of three elements: (1) regional projects that address the uncertainty in seismic source zone configurations and seismic energy propagation; (2) topical projects that deal with developing site-specific spectra, strong ground-motion models, and soil failure models; and (3) probabilistic projects that deal with techniques to handle the uncertainties.

Seismic Margins - Research to assess the inherent seismic margin in nuclear power plants. In this context, margin is defined as the capability of a plant to sustain an earthquake larger than its safe shutdown earthquake. The NRC Seismic Design Margins Program is developing

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review procedures and screening guidelines based on the results of previous and ongoing research (for example, probabilistic risk assessments and piping, component, and building dynamic tests) to assess seismic vulnerabilities and evaluate the seismic margin of operating nuclear plants.

Fragilities and Response - Research to predict the behavior of structures, systems, and components subjected to seismic loads within and beyond their design basis, that is, seismic loads causing inelastic or nonlinear response. This research is reducing the large uncertainty in the fragility or failure data base used in seismic vulnerability and seismic margin studies. Response and/or fragility data will be obtained on structures, components, piping, and dams and embankments.

Validation - Research to validate experimentally the calculational methods used in probabilistic risk assessments, seismic vulnerability assessments, and seismic margins studies. The research efforts involve cooperative research programs using large foreign test facilities in order to maximize the return from available resources. As such, cooperative efforts through the Electric Power Research Institute with Taiwan and independent efforts with West Germany and Japan have been established.

This plan describes the safety issues, regulatory needs, and the research necessary to address these needs. The plan also discusses the relationship between current and proposed research within the NRC and research sponsored by other government agencies, universities, industry groups, professional societies, and foreign sources. The aims of the Seismic Safety Research Program are to support NRC licensing decisionmaking and to maximize the utilization of research findings from all data sources through changes in rules, regulatory guides, and standard review plan sections.

The NRC Office of Nuclear Reactor Regulation (NRR) research needs in seismic analysis methodology are described in an April 8, 1982 memorandum from H. R. Denton to R. B. Minogue (Ref. 8) and an October 3, 1986 memorandum from H. R. Denton to E. S. Beckjord (Ref. 9). Additional needs in seismic-related research are identified during NRR's input and review of the Long-Range Research Plan (Ref. 10). Other needs in seismic research are contained in correspondence between the Advisory Committee on Reactor Safeguards (ACRS) and the NRC staff on the quantification of seismic design margins (Refs. 11 through 14) and a Commission Policy Statement (SECY-86-162) on the inclusion of external events in the implementation of the Severe Accident Policy Statement (Ref. 15).

The seismic issues, regulatory needs, and research objectives are described in Section 2. The projects to meet the regulatory needs and research objectives are described in Section 3 of this plan and are composed of the following:

1. Seismotectonic Program - research to quantify and reduce the uncertainty in seismic hazard assessments and to develop methods of dealing with the related uncertainties;

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2. Soil Response Program - research to assess the potential for soil failure (settlement or liquefaction) at nuclear power plant sites subjected to earthquakes at and above the Safe Shutdown Earthquake;

3. Seismic Category I Structures Program - analytical and experimental research to reduce uncertainties and provide accurate estimates of how noncontainment structures transmit loads from earthquakes larger than the design basis to safety systems and components;

4. Containment Failure Modes Under Seismic Loads Project - research to reduce uncertainties and provide accurate estimates of containment performance in a severe accident if the accident were initiated by a large earthquake;

5. Dams and Embankments Project - analytical and experimental research to reduce uncertainties associated with the dynamic analysis of dams and embankments;

6. Structural Damping Project - analytical and experimental research to reevaluate the damping values currently recommended for concrete and steel and establish damping coefficients associated with inelastic structural response;

7. Piping Design Program - analytical and experimental research to reduce uncertainties in determining response and failure modes and to develop more realistic design criteria resulting in balanced safety between operation and accident conditions;

8. Seismic Component Fragility and Ruggedness Project - analytical and experimental research to reduce uncertainties associated with predicting the earthquake level (magnitude) at which critical electrical and mechanical equipment fail to perform their safety functions;

9. Validation of Seismic Calculational Methods Program - analytical and experimental cooperative research, using large foreign test facilities, to reduce uncertainties in computer codes used to predict the response, particularly in the nonlinear range, of structures, systems, and components;

10. Standard Problems for Structural Computer Codes Project - analytical research to establish problems with experimentally known solutions (benchmarks), thereby reducing uncertainties associated with the transmittance of earthquake loads through the soil to safety-related buildings;

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11. Post-Earthquake Inspection Project - research to develop inspection requirements and acceptance criteria for use in determining the operability of a nuclear power plant subjected to an earthquake larger than the Operating Basis Earthquake;

12. Exchange of Seismic Research Information Project - an exchange with the Japan Agency of Natural Resource and Energy on information related to nuclear power plant regulation and safety;

13. Seismic Design Margins Program - research to develop and improve guidance for assessing the inherent capabilities of nuclear power plants to withstand earthquakes above the design level and to provide an effective and efficient means to identify seismic vulnerabilities; and

14. Reliability Analysis of Nonlinear Behavior of Concrete Structures Project - analytical research to reduce uncertainties associated with predicting the behavior of structures subjected to seismic and other loads greater than their original design.

Figure 1 shows the program/project interrelationships and regulatory applications. Project integration is the responsibility of the NRC Office of Nuclear Regulatory Research (RES).

In the areas of containment and piping research, this plan is only addressing the seismic aspects of the NRC research program. A description of NRC piping and containment research can be found in NUREG-1222, "Piping Research Program Plan," and NUREG-1264, "Containment Integrity Research Program Plan" (both plans are unpublished).

A glossary containing the acronyms and definitions of seismic-related terms used in this plan is provided as well as references and a bibliography of project-related reports.

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FOREIGN AND DOMESTIC RELATED PROGRAMS

Earth Sciences

- EPRI and Industry Probabilistic Seismic Hazard Program
- USGS Ground-Motion Studies
- National Earthquake Hazard Reduction Program (USGS, NSF, FEMA, NBS)
- Corps of Engineers Seismic Soils Settlement Program

Seismic Margins

- EPRI Seismic Margins Research Program
- Industry Probabilistic Risk Analyses

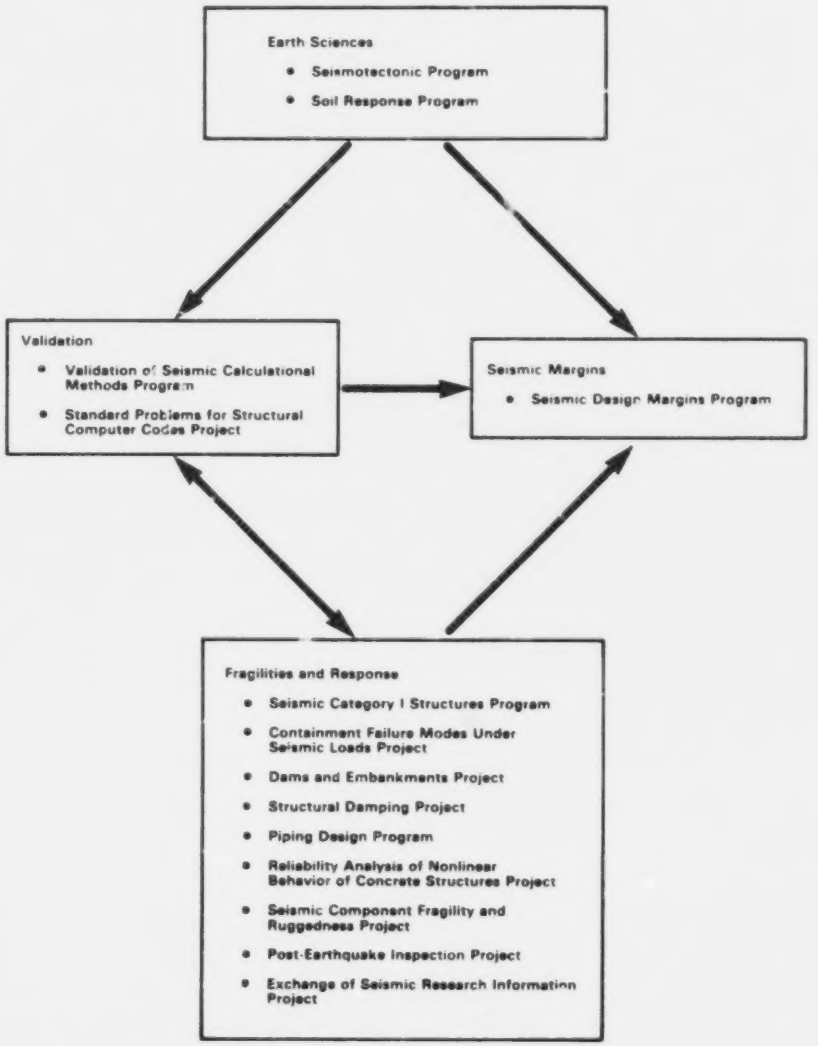
Fragilities and Response

- EPRI Piping Program
- EPRI Equipment Qualification Program
- Seismic Qualification Utilities Group
- NRC Equipment Qualification Program
- NRC Aging Program
- NRC Piping Research Program
- NRC Containment Integrity Research Program

Validation

- Germany - KfK HDR Program
- EPRI - Taiwan SSI Experiments
- Japan - MITI/NUPEC Seismic Experiments at Tadotsu

NRC SEISMIC SAFETY RESEARCH PROGRAM


Earth Sciences
• Seismotectonic Program
• Soil Response Program
Validation
• Validation of Seismic Calculational Methods Program
• Standard Problems for Structural Computer Codes Project
Seismic Margins
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Fragilities and Response
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• Dams and Embankments Project
• Structural Damping Project
• Piping Design Program
• Reliability Analysis of Nonlinear Behavior of Concrete Structures Project
• Seismic Component Fragility and Ruggedness Project
• Post-Earthquake Inspection Project
• Exchange of Seismic Research Information Project

Figure 1 Project interrelationships and Regulatory Applications

REGULATORY APPLICATIONS

Earth Sciences

- Charleston, New Brunswick, and Ohio Earthquake Issues
- Design Response Spectra (R.G. 1.60)
- Site-Specific Spectra
- 10 CFR Part 100, Appendix A
- Generic Issue 119, Piping Review Committee Recommendations (OBE-SSE Decoupling)

Seismic Margins

- Licensee Seismic Issues
- Severe Accident Policy Statement Implementation

Fragilities and Response

- Licensee Seismic Issue
- Pipe Damping (R.G. 1.61)
- ASME Code - Piping and Structures
- Independent Pipe Support Motion
- Floor Response Spectra (R.G. 1.122)
- Structural Damping (R.G. 1.61)
- Generic Issue 119, Piping Review Committee Recommendations (Piping Criteria)
- USI A-40, Seismic Design Criteria
- Post-OBE Inspection and Restart Criteria

Validation

- Licensee PRA Review
- Licensee Seismic Issues
- USI A-40, Seismic Design Criteria

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2. ISSUES, REGULATORY NEEDS, AND RESEARCH OBJECTIVES

The seismic issues, regulatory needs, and research objectives are divided into six categories: uncertainties in seismic hazard, earthquakes larger than the design basis, seismic vulnerabilities, shifts in building frequency, piping design, and adequacy of current criteria and methods. Whereas these issues, needs, and objectives are discussed from the NRC perspective, the NRC is not alone in sponsoring research addressing these related areas. Seismic safety research is being performed by other organizations within the United States (e.g., the Electric Power Research Institute (EPRI) and the United States Geological Survey (USGS)) and in other countries (e.g., Japan and the Federal Republic of Germany) with several joint projects and significant interaction and cooperation in project planning.

2.1 Uncertainties in Seismic Hazard

2.1.1 Issue

The fundamental seismic hazard issues are how to quantify and to reduce the uncertainties in seismic hazard assessments and how to develop techniques to deal with the uncertainties in a regulatory environment. Factors that contribute to the uncertainty in the seismic hazard assessment are (1) the uncertainty in establishing seismic source zones and their earthquake potential, (2) the uncertainty in the propagation of seismic energy, and (3) the uncertainty in the site-specific ground-motion response, including soil response.

In addition to the fundamental seismic hazard issues, the issue of the possible recurrence of an 1886 Charleston-sized earthquake anywhere on the eastern seaboard has commanded significant NRC attention. In November 1982, the USGS clarified its position with respect to the 1886 Charleston earthquake (Ref. 16). The clarifying statement represents not so much a new understanding but rather a more explicit recognition of existing uncertainties with respect to the causative structure and mechanism of the 1886 Charleston earthquake. Many hypotheses have been proposed for the seismogenic mechanisms and potential location on the eastern seaboard of future Charleston-sized earthquakes. Some of these hypotheses would limit such an earthquake in both size and location while others would allow this earthquake to occur over very large areas of the Eastern United States and Canada. Presently, none of these hypotheses is definitive, and all contain strong elements of speculation.

Also, a Policy Issue memorandum for the Commissioners (SECY-82-53, February 5, 1982) on the January 9-11, 1982 New Brunswick, Canada, earthquake (Ref. 17) stated in part: "Although all information relating to the size and location of the event is preliminary, it eventually may be concluded that this earthquake could have occurred anywhere within the New England Piedmont Tectonic Province and in accordance with Appendix A to 10 CFR Part 100, would represent the largest historical earthquake in that province....which includes much of New England and southern New York."

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In light of Appendix A to 10 CFR Part 100, one interpretation of the Charleston and New Brunswick earthquake could result in controlling earthquake ground motions being significantly greater than their original design values at some Eastern and Central U.S. nuclear power plants. The Commission could be faced with requiring significant reanalysis to verify existing margins and/or extensive structural and equipment modifications to meet the desired safety level.

2.1.2 Regulatory Needs

1. Collection of data concerning seismic source zones in the Central and Eastern United States, including Charleston, New Madrid, and New England. Also, collecting data concerning seismic energy propagation in the East as a basis for evaluating seismotectonic provinces. This information will be necessary in revising Appendix A to 10 CFR Part 100 and related regulatory guidance. Except for the New Madrid seismicity, the distribution of seismicity in the East is not well defined. No working hypothesis for the cause of the seismicity is generally accepted by the geoscience community. In addition, continued seismic monitoring in the Central and Eastern United States is needed by the NRC to support its regulatory functions with regard to operating nuclear power plants. Therefore, the NRC will continue to support the regional seismographic networks through 1992, during which time the USGS will, in cooperation with the NRC, install and initiate operation of a new seismographic network in the Central and Eastern United States.

2. An information base of site-specific response spectra as a basis for amendments to Appendix A to 10 CFR Part 100 and related regulatory guidance. Recent earthquakes such as those in New Brunswick, New Hampshire, and Ohio have generated important strong-motion records that for the first time provide a significant opportunity to compare real data with theoretical ground motion and attenuation models for the Central and Eastern United States. Analysis of these records will address important regulatory questions concerning the interpretation of this type of record and its use in licensing decisions.

3. Methods for handling the uncertainties in assessing the potential risk from seismic hazards for use in revising current siting regulations. This program should include such topics as assessment of the applicability of using different methods of seismic hazard analysis, evaluation of the impact of the 1986 Ohio and 1982 New Brunswick earthquake sequences, and the verification of Holocene movement on the Meers Fault. The current seismic siting regulations do not provide guidance on how to handle the large uncertainty associated with the predictions of seismic phenomena. Decisions must be made on the best available data. There is a need to develop statistical or probabilistic tools to aid the decisionmaking process.

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4. Determination of the cause of high-frequency energy observed in recent Eastern and Central United States earthquakes. High-amplitude, high-frequency accelerations of limited duration were recorded in several recent studies, e.g., New Brunswick, Monticello Reservoir, and Ohio earthquakes. These high-amplitude, high-frequency accelerations are not enveloped by Regulatory Guide 1.60 design spectra. It is necessary to determine whether the high-frequency exceedance is due to the earthquake source, path effects, or local site conditions.

5. Improvement of the data base and analysis techniques for predicting soil failure, particularly soil liquefaction. These should focus particularly on small or moderate changes in the acceleration value at which the design spectrum is anchored. The recent high acceleration records from New Brunswick, New Hampshire, and Ohio and the potential for increased design spectra accelerations because of the Charleston earthquake issue may reduce the safety margins associated with current soil-failure-prediction techniques.

6. Verification of methods for predicting seismic soil settlements. The consequences of soil settlement, liquefaction, or soil failures at earthquake levels above the Safe Shutdown Earthquake could be a significant contributor to overall risk. Current probabilistic risk assessments (PRAs) do not adequately address this problem, and at the present time there are no verified methods for estimating seismic soil settlement.

2.1.3 Research Objectives

1. Improve methods and data base for assessing the seismic hazard of the Eastern and Central United States sites.

2. Develop an understanding of high-frequency content of earthquakes, particularly Eastern and Central U.S. earthquakes, including an assessment of the potential for even greater exceedance in future more energetic events.

3. Reduce uncertainties related to seismic hazards and seismically induced soil liquefaction and settlement.

2.2 Earthquakes Larger Than Design Basis

2.2.1 Issue

Frequently the NRC is faced with decisions related to the seismic design basis of operating plants. For example, a better understanding of seismicity may result in the prediction of higher seismic loads, thereby necessitating a reevaluation of the seismic capacity of the components and structures of the

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plants. The seismic margin issue addresses whether changes in the seismic design basis can be accommodated within the inherent capacity of the original design or whether plant modifications are necessary.

A sound, practical seismic margins program using the margins-to-failure concept and systems analysis techniques can serve to minimize the need for changing requirements and licensing actions in response to changing estimates of the seismic hazard and system response. In addition, seismic margin studies can provide a sound basis for establishing confidence in the seismic capacity of nuclear power plants and serve to identify contributors to seismic risk.

2.2.2 Regulatory Needs

1. Methods and procedures to assess systematically the ability of a nuclear power plant to withstand earthquakes greater than its design bases. Nuclear power plants traditionally have been designed using conservative methods and criteria to enable safe shutdown after a design basis earthquake. Although ensuring design adequacy, this deterministic approach does not give a true picture of the actual margin to failure, nor does it provide enough information to make realistic estimates of seismic risk. From a licensing perspective, there is a continuing need for consideration of the inherent quantitative margin against failure from earthquakes because of the changing perceptions of the seismic hazard. Reevaluation of plant seismic resistance using methods similar to current design practice requires a rigorous reanalysis of systems, structures, and components even if slight increases in the earthquake level are proposed. These reevaluations, performed each time a new earthquake level is proposed, entail a great effort by both the utility and licensing staff, even if no plant modifications are made. Although ensuring design adequacy at the new earthquake level, these reevaluations do not identify or quantify the margin to the earthquake level where public safety is compromised. An alternative review methodology that relies both on seismic PRA information and on test and earthquake experience data needs to be developed. It should minimize the amount of analysis needed to assess the seismic resistance of structures and components and give a thorough overall picture of plant seismic capacity.

2. Improved data bases of seismic response and fragility for structures and mechanical and electrical equipment. The response and fragility data used in the current licensing criteria, PRAs, and seismic margin evaluations rely heavily on expert opinion and modeling assumptions. A better understanding is needed of response and failure modes and levels, and the parameters that control them (e.g., soil-structure interaction, location of seismic input control point, damping values), as a basis for assessing inherent margins in seismic design.

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2.2.3 Research Objectives

1. Develop procedures to assess the ability of nuclear power plants to withstand earthquakes greater than the design basis.

2. Develop seismic response and fragility (capacity) data for structures, mechanical and electrical equipment, and facilities outside the plant structure (e.g., heat sinks, external piping, foundations).

3. Verify procedures to compute fragilities or seismic capacities in seismic risk and margin assessments, and obtain and synthesize test and experience data to replace rigorous analytical estimates.

2.3 Seismic Vulnerabilities

2.3.1 Issue

To achieve the main goal of the Severe Accident Policy Statement, which is to bring stability to licensing and regulation with regard to all severe accident issues, it is important that all initiators of severe accidents receive appropriate consideration. The policy statement includes events initiated within the plant and events caused by external initiators such as earthquakes and floods. With regard to external events, the identification of seismic vulnerabilities could be of utmost importance.

A procedure based on seismic PRA technology and seismic margin screening guidelines will identify relevant structures, components, and systems that have failure levels below conservatively established acceptance criteria and have seismic vulnerability. A more detailed review would establish the plant's seismic capacity.

2.3.2 Regulatory Need

Data and procedures to identify those components and systems of nuclear power plants that make the plants most vulnerable to earthquakes greater than the design bases. Seismic margin reviews will eliminate the need to evaluate the seismic capacity of many components or systems because they have failure states above those associated with an important plant safety function. Safety function importance has been established by reviewing available seismic PRAs. For those systems and components that are identified as being vulnerable to seismic events, procedures must be established to estimate this seismic capacity. Response and fragility data are needed to aid in seismic capacity assessments since structures and mechanical and electrical equipment may experience inelastic behavior. Plant components have to be assessed for these conditions.

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2.3.3 Research Objectives

1. Develop and/or verify procedures to identify and assess seismic vulnerabilities of nuclear power plants.

2. Provide data to evaluate the need for including seismic events in severe accident policy implementation.

2.4 Shifts in Building Frequency

2.4.1 Issue

Two important and consistent observations have been made from the static and dynamic test data of reinforced concrete shear wall and building models. First, the scalability of the results obtained from different size models, fabricated with microconcrete and actual material, to prototypical buildings has been demonstrated in the elastic and inelastic response range. Second, the structural stiffness (load-deflection relationships) of these models is lower than analytical predictions (based on an uncracked cross-section strength-of-materials approach) by a factor of four, leading to frequency predictions being low by a factor of two.

2.4.2 Regulatory Need

Assessment of how the shift in the fundamental frequency of structures affects equipment and piping design and plant risk. The reduction of first mode frequency, which is associated with the reduction in stiffness, retunes the structure relative to the seismic input. As a result, actual floor response spectra may differ from those used as the design basis. It is important to understand how this affects equipment and piping mounted at various floor levels in the structure and ultimately the plant risk. If equipment and piping is mounted such that its frequency is less than the original (design) structural frequency, it could be tuned to the structure's resonance as a result of this frequency shift.

2.4.3 Research Objectives

1. Perform experiments and analysis to determine if the differences in structural stiffness are principally due to the models tested, interpretation of test data, or shortcomings in standard analytical procedures.

2. Assess how shifts in structural frequency affect the design of equipment and piping and plant risk.

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2.5 Piping Design

2.5.1 Issue

Earthquake experience data, dynamic tests, and analytical studies have shown that piping can resist dynamic loads much larger than its design limits. In fact, seismic PRAs and margin studies typically ignore reviewing piping systems except to check for adequate anchorage, system interactions, and certain cases of extreme relative displacements between piping support locations.

While piping seismic inertial loads are generally not thought to be large risk contributors, significant regulatory attention and effort are spent in their evaluation. There are a number of reasons. First, piping dynamic analyses are relatively complex requiring decisions on appropriate damping values, modal methods, and dynamic load combinations. Second, the conservatisms involved in dynamic piping design are not well understood, particularly with regard to actual failure mechanisms. Third, since the current design process requires evaluation of all piping locations for all loads and load combinations, the mere quantity of safety-grade piping in nuclear power plants (on the order of 10 to 50 miles) makes each aspect of its design significant.

A major concern of the USNRC Piping Review Committee was the overdesign of piping systems for dynamic inertial loads. Unlike the design of most other nuclear plant components and structures, the design of piping for dynamic inertial loads can significantly affect thermal expansion loading and exacerbate problems associated with the reliability of snubbers. Recognizing this, the Piping Review Committee recommended a number of regulatory and research activities to reduce the excess conservatisms in piping dynamic load design. Progress has been made, especially in the area of damping criteria. However, additional work is still needed, particularly to support changes to ASME Code piping stress criteria to recognize different, more probable, dynamic failure mechanisms than were previously considered in the Code.

2.5.2 Regulatory Needs

1. Data defining actual piping response and failure behavior due to high-level dynamic input. These data should establish design margins and justify changes to current design criteria. These data are best obtained through experimental rather than analytical means since previous assumptions about dynamic failure mechanisms now appear to be incorrect. For example, dynamic ratchetting and fatigue appear more likely to lead to failure than cross-sectional plastic collapse.

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2. Investigation of potential changes in design rules for piping supports and nozzles. A thorough assessment of earthquake experience data should also serve to support new design rule changes for piping systems.

3. Quantify and understand all the uncertainties and conservatisms that go into the piping design process. There are ongoing licensing staff needs to assess the cumulative effects of combinations of proposed criteria changes, particularly for the use of new pipe damping criteria (Code Case N-411) and other new response calculation techniques.

2.5.3 Research Objectives

1. Assess uncertainties and conservatisms in piping dynamic load design, and evaluate the cumulative effect of proposed piping criteria changes.

2. Obtain and evaluate test and experience data on piping dynamic response and failure to support improvements in current piping design criteria.

3. Obtain and evaluate test and analysis data on piping nozzle flexibility and design to support improvements to nozzle design guidance.

4. Evaluate current piping support design criteria, provide the basis for improving support and overall piping system design, and assess the adequacy of proposed design techniques using energy-absorbing supports.

2.6 Adequacy of Current Criteria and Methods

2.6.1 Issue

During their development, the current seismic design criteria were based on state-of-the-art knowledge supplemented by judgments and conservative assumptions where physical data were lacking. Thus, there is a significant tendency for the seismic design criteria to be conservative and in some cases overly conservative to the point where there has been an adverse effect on plant safety (e.g., the case of an excessive use of piping supports). However, the judgment and assumptions that are incorporated in the current seismic design criteria should be confirmed and the validity and/or consequences of new data assessed so that the safety of operating plants can be ensured. Furthermore, the margins in both the individual and combined parts of the seismic design process are often not well understood. As individual seismic design questions arise, the adequacy of design criteria has to be reassessed.

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2.6.2 Regulatory Needs

1. There is a continuing need to evaluate current seismic design criteria, analysis procedures, and the effects of uncertainties to assess the overall effects of new information on the seismic design process. This need is not addressed through a rigorously defined program but is done on an ad hoc basis as specific technical questions and new data develop. Future concerns may cover items that are nominally classified as nonseismic. For instance, the aging research program (Ref. 18) may uncover important degradation mechanisms not considered in seismic design and seismic PRA and margins evaluation. The importance of the effect of these aging mechanisms will need to be assessed in the context of component, system, and plant earthquake behavior.

2. Information on the significance of the energy content and duration of high-frequency, high-acceleration earthquakes. The Regulatory Guide 1.60 spectral shape does not envelop high-acceleration, high-frequency earthquakes similar to those shapes obtained from the January 31, 1986 earthquake at the Perry Nuclear Power Plant. Some of these recorded accelerations exceeded the Operating Basis Earthquake and the Safe Shutdown Earthquake design spectra at high frequencies (above 15 Hz). It is necessary to understand the significance of these high-frequency data on structure, system, and component responses and to provide a basis for developing criteria.

3. Basis for development of procedures to inspect nuclear power plant structures and systems following an earthquake. Nuclear power plants must shut down for inspection whenever the Operating Basis Earthquake is exceeded. Procedures are needed to define Operating Basis Earthquake exceedance, provide plant shutdown criteria, and assess the extent of earthquake-induced damage to mechanical and structural systems to determine if degradation has occurred and whether plant operation can continue or resume.

2.6.3 Research Objectives

1. Perform analysis and experiments to evaluate current seismic design criteria and analytical procedures where specific needs have been identified.

2. Determine the significance of high-amplitude, high-frequency earthquakes on structure, system, and component responses.

3. Develop procedures to perform a post-Operating Basis Earthquake evaluation.

4. Develop the basis for defining the Operating Basis Earthquake in a manner consistent with its purpose and not necessarily with a relationship to the Safe Shutdown Earthquake.

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3. PROJECT DESCRIPTION

The following is an executive summary of the project descriptions. More detailed descriptions for most of these projects are contained in appendices to this plan or other NRC research plans. Each of these project descriptions includes the following sections:

1. Title - An identifier for the research area. If provided, the parenthetical statement following the title refers to appendices to this plan or other NRC NUREG reports.

2. Scope - A brief description of the program or project and how it addresses the research objectives. Parenthetical statements, e.g., (2.1.3.1), identify the research objective being addressed.

3. Integration and Relationship With Other Research - A description of how the programs or projects included in this plan are integrated to address the research objectives. Also included is a description of the pertinent research and development being performed by other government agencies, universities, industry groups, professional societies, and foreign sources.

4. Products - Research products and expected completion dates. The regulatory needs addressed are indicated in parentheses, e.g., (2.1.2.1).

5. Regulatory Application - Rules, regulatory guides, standard review plan sections, generic issues, etc., affected by this research.

3.1 Seismotectonic Program (Appendix A)

3.1.1 Scope

The uncertainty in the characterization of seismic source zones is the factor addressed by the regional program, which includes projects investigating features within specific regions. The uncertainty arises from several aspects such as delineation of the seismic source zone, estimation of the maximum credible earthquake, characterization of source parameters, and occurrence relationships.

The regional seismographic networks are the mainstay of the regional program. They provide the basic seismological data set on the recent occurrence of earthquakes, their locations, depths, magnitudes, slip orientations, recurrence rate/interval, and source parameters, including generation of high-frequency acceleration (2.6.3.4). They also provide important information on the propagation of seismic energy over distance. They guide the siting of supplementary geological/geophysical investigations on seismically active structures (2.1.3.1). They also serve the fundamental function of monitoring the seismicity and any changes in the patterns of seismicity. (The regional seismographic networks in the Central and Eastern United States are currently

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largely supported by the NRC. Over the next 6 years the NRC and the U.S. Geological Survey (USGS) will establish a National Seismographic Network to be operated and maintained by the USGS to serve the seismicity surveillance function) (2.1.3.1 and 2.1.3.2).

The topical element of the Seismotectonic Program addresses the seismic hazard uncertainties that are not identified with a specified source zone or that cover several source zones, such as seismic energy propagation, including higher frequency energy, site-specific spectral analysis, and soil settlement resulting from liquefaction (2.1.3.1, 2.1.3.2, and 2.1.3.3).

The resolution of this set of issues generally requires additional data and their analysis and interpretation. The uncertainty in seismic energy propagation is a reasonable example to consider. The seismographic networks are recording the basic data required, which are seismic energy amplitudes and frequencies at many distances over many travel paths for numerous earthquakes. The basic data need to be correlated and analyzed to develop models to predict the attenuation of ground motion with distance from specific source zones. This topic is being investigated by several network operators covering large areas such as the Southeastern United States.

The probabilistic element of the Seismotectonic Program is associated with seismic hazard assessments and addresses topics that are not amenable to short-term resolution but for which there are pressing regulatory requirements for interim positions. This research generally takes the form of development of probabilistic techniques for the analysis of existing data sets. The recently completed Seismic Hazard Characterization Project (SHCP) is an excellent example of this type of research. The issue of the recurrence of a Charleston-sized earthquake on the Atlantic seaboard is a seismic zonation issue that has been under active investigation for about 10 years, and a resolution is still not in sight. The SHCP was undertaken to provide the licensing office with a screening tool to determine which eastern nuclear power plants may require reanalysis of their seismic designs and to provide criteria for setting priorities for that reanalysis (2.1.3.1).

3.1.2 Integration and Relationship With Other Programs

The Seismotectonic Program provides the basic geoscience data used to guide the other research programs in the seismic area. For example, this program provides the ranges of ground-motion accelerations that are appropriate for initial inputs to the NRC Soil Response Project (3.2 and Appendix B). Products (guidance) from the Seismotectonic Program when coupled with the Seismic Design Margins Program (3.13 and Appendix G) will provide insights into the adequacy of current regulatory criteria and the ability of an existing nuclear power plant to sustain an earthquake larger than the design basis.

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In addition to research in seismic hazard assessment funded solely by the NRC, the NRC jointly funds a number of cooperative research projects with other Federal, State, and foreign agencies. Establishment of a National Seismographic Network with the USGS and a project to study the propagation of seismic strong ground motion through a soil column with the French Atomic Energy Commission, the USGS, and the U.S. Army Corps of Engineers are two important examples of cooperatively funded research.

Other Federal, State, and industrial organizations are also independently funding and conducting this type of research. Notably, the Federal Emergency Management Agency, the USGS, the National Science Foundation, and the National Bureau of Standards are the Federal participants in the National Earthquake Hazard Reduction Program. Because of higher levels of seismic activity, these principal Federal efforts give emphasis to the Western United States. The State geologic surveys make a significant contribution through their programs of regional hazard mapping and assessments. Industry, in general, and the public utilities, in particular, have conducted programs in hazard assessment. The Electric Power Research Institute (EPRI) has instituted a major effort on estimating the seismic hazard at nuclear power plant sites. The Corps of Engineers is concerned with seismic hazard primarily as it affects their structures. They have produced a seismic hazard map of the Central United States and are working on one for the eastern seaboard.

3.1.3 Products

a. Seismographic network data used on a day-to-day basis by licensing staff, by staff involved in probabilistic risk assessments (PRAs), by the regional seismic hazard characterization projects (this includes addressing the source and propagation of high-frequency, high-amplitude accelerations), and for rulemaking decisions and engineering research projects (1987-1992). (Supports regulatory needs 2.1.2.1, 2.1.2.3, and 2.1.2.4.)

b. Geophysical data for determining crustal structure in areas of suspicious geologic structures to be used on a day-to-day basis by licensing staff, by staff involved in PRAs, by the regional seismic hazard characterization projects, and for rulemaking decisions and engineering research projects (1987-1992). (Supports regulatory need 2.1.2.1.)

c. Preliminary techniques for calculating site-specific response spectra to be used by the licensing staff and for rulemaking decisions (1989). (Supports regulatory need 2.1.2.2.)

d. Study of the various theories for the causes of seismicity in the Eastern United States to be used on a day-to-day basis by the licensing staff and for rulemaking decisions (1990). (Supports regulatory need 2.1.2.3.)

e. Validation of calculations assessing site-specific acceleration levels used to develop some of the Seismic Qualification Utilities Group damage/fragility data base (1988). (Supports regulatory need 2.1.2.2.)

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3.1.4 Regulatory Application

The results from the Seismotectonic Program will be used as a basis for a probable revision of Appendix A to 10 CFR Part 100, "Seismic and Geologic Siting Criteria for Nuclear Power Plants," which will aid in resolving Generic Issue 119, Piping Review Committee Recommendations (decoupling OBE from SSE). They will also be used to resolve the Charleston earthquake issue, i.e., the potential occurrence of an earthquake the size of the 1886 Charleston earthquake anywhere on the eastern seaboard. The results from the study of high-frequency, high-amplitude accelerations from small earthquakes will be used to assess the need to change Regulatory Guide 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants."

For ongoing licensing activities, the analysis of data gathered by geological, seismological, and geophysical research will be used as the bases for probability risk analyses and as the basis for determining whether reevaluating the seismic designs of operating nuclear power plants is necessary. More specifically, the data will be used to delineate seismic source zones, define seismogenic structures at hypocentral depths, determine the ground-motion propagation characteristics of rocks and soils between the earthquake source and a given site, and determine site-specific effects. Studies of paleoseismic features will be used to estimate the magnitudes and levels of ground motions of prehistoric earthquakes and to determine more accurate recurrence intervals for moderate to large earthquakes by extending the seismic record back in time.

3.2 Soil Response Program (Appendix B)

3.2.1 Scope

The fundamental regulatory issue that needs to be addressed regarding the geotechnical engineering aspects of nuclear power plant facilities concerns the seismic stability of the plant foundation soils when subjected to seismic loads up to or greater than the Safe Shutdown Earthquake (2.1.3.3). Most dynamic analysis techniques presently in use for determining soil response to earthquakes are based on total stress methods. Deformations of soil are, however, controlled by effective stress. Until recently, no dynamic effective stress analysis techniques existed for lack of a model to predict the parameter pressures developed by seismic loading. As a result, soil settlement and liquefaction due to earthquakes could not be accurately predicted. This research is therefore focused on establishing a data base and improving the analysis techniques by using a validated dynamic effective stress model to predict soil response to seismic motion.

Three research projects address the uncertainties inherent in modeling the major variables influencing soil response to earthquake motions such as nonlinear pore pressure generation and dissipation, strain softening from reduced effective stress, and decrease in shear modulus (2.1.3.3). In the first of these projects, which is being conducted by the U.S. Army Corps of Engineers, a verified nonlinear, two-dimensional model capable of computing

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settlement, porewater pressure response histories, and motions due to earthquake excitation has been developed. Validation of the two-dimensional model was accomplished by analyses of data on the behavior of the prototype from geotechnical centrifuge testing of structures simulating large structures such as those at nuclear power plants. The next phase of the project will involve three-dimensional interactive effects and differential responses of sites containing structure complexes such as those at nuclear power plant sites, which involve various geometries, loading, and interconnections between structures.

In the second and related project, which is being conducted through the National Science Foundation, stability failures at waterfront structures such as cooling water intake structures at nuclear plant sites are being studied (2.1.3.3). These failures. which occur some time after the end of earthquake ground shaking, result from the liquefaction of saturated sand adjacent to the structure and are caused by the redistribution of pore pressures and localized volume changes within the mass of sand during and following an earthquake. This research will lead to a better understanding of delayed failures, primarily concerning the amount of compaction and the final desirable void ratio of the sand behind the structure to prevent delayed liquefaction failure.

The third research project will be a field validation study of the assumptions used in theoretical analyses of the passage of seismic waves from bedrock to the overburden (2.1.3.1, 2.1.3.2, and 2.1.3.3). There is a critical lack of this type of data. Several deep boreholes will be thoroughly instrumented in both crystalline bedrock and overlying soil in an area near Anza, California, where a Richter size earthquake of magnitude 6.5 is expected in the near future. The data will be interpreted and analyzed and comparisons made with existing convolution and deconvolution analysis models. This program will complement the two programs discussed earlier in that it will better define the spatial variation of earthquake motions. The latter can be input into the two-dimensional and three-dimensional validated dynamic effective stress models (discussed in the preceding section) for computing seismic settlement and liquefaction and porewater pressure histories. (See Appendix A for details concerning the tectonic implications of this study.)

3.2.2 Integration and Relationship With Other Research

This program will provide the staff with validated and verified dynamic effective stress two-dimensional and three-dimensional models to accurately evaluate seismic liquefaction and settlement of nuclear power plant systems, structures, and components subjected to earthquakes equal to and larger than the Safe Shutdown Earthquake. It will lead to a better understanding and help in reducing the possibility of stability failures due to delayed liquefaction effects at waterfront structures such as cooling water intake structures at nuclear power plants. Seismic hazard analysis methods will be vastly improved by incorporating field-validated seismic wave propagation characteristics (from the Anza, California, project) from the bedrock to the overburden in the

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seismic wave attenuation models. Further improvements in the seismic hazard analysis will include the evaluation of liquefaction potential and the quantification of liquefaction risk at nuclear power plant sites.

The program will need ground-motion amplitude intensity, duration, and cycles of loading, particularly on the eastern seaboard. The geometry of seismic source zones will be required as well as the attenuation characteristics of the earthquake motions. The program as a whole will complement and be used in the development of the Seismic Design Margins Program to evaluate the seismic margins available in soil-structure interaction and response studies.

Computer programs have been developed at the University of British Columbia, Vancouver, Canada, for the computation of the probability of seismically induced liquefaction. The method combines Seed's simplified method with seismic hazard analysis. In situ testing techniques using Raleigh waves are currently being employed at several sites in the Imperial Valley of California to predict the potential for liquefaction and to analyze sites already liquefied. This technique was developed at the University of Texas and uses a fast Fourier transform and spectral analysis, which with inversion calculates the shear wave velocity, shear modulus, and layering of the media.

A project jointly funded by the NRC, EPRI, and the Taiwan Power Company (Taipower) is in progress in a high seismic region in Taiwan where a strong motion array network is located (3.9 and Appendix E). The specific objectives of the project are to obtain free field earthquake data, obtain earthquake-induced containment response data on 1/4-scale and 1/2-scale models of PWR containment structures, and evaluate soil-structure interaction, containment response, and component response under various earthquake environments.

The Federal Ministry for Research and Technology, West Germany, has been using the HDR superheated steam reactor at Kahl for safety research since 1973 (3.9 and Appendix E). Some of the ongoing validation studies include observations of some limited soil-interaction phenomena. The University of Cambridge, England, is involved extensively in researching earthquake behavior of soils and soil-structure interactions by obtaining prototype behavior in a geotechnical centrifuge with earthquake loading. In the centrifuge-reduced geometrical scale, prototype conditions, including actual stress, strain, and response, occur under increased acceleration of simulated gravity. The university is also collaborating with the Massachusetts Institute of Technology in technology transfer in areas of soil-structure interaction. One such collaboration is a program funded by NRC on the seismic stability of waterfront structures.

3.2.3 Products

a. Verified and validated nonlinear, two-dimensional, soil-structure interactive dynamic effective stress model that computes seismic settlement, porewater pressure histories, and spatial variation of seismic acceleration (1987-1988). (Supports regulatory needs 2.1.2.5 and 2.1.2.6.)

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b. Verified and validated nonlinear, three-dimensional soil-structure interactive dynamic effective stress model that computes seismic settlement, porewater pressure histories, and spatial variation of seismic acceleration (1988-1990). The three-dimensional model is an improvement on the two-dimensional model (see a. above) and accounts for the differential responses of sites containing structures with various geometries, loading, and interconnections, e.g., piping, between structures. (Supports regulatory needs 2.1.2.5 and 2.1.2.6.)

c. Detailed analysis and interpretation of geotechnical centrifuge tests to obtain answers to questions on the delayed stability failure of waterfront structures (such as cooling water intakes at nuclear power plant sites) resulting from the redistribution of pore pressures and localized volume changes within sand during and following an earthquake (1988-1989). (Supports regulatory needs 2.1.2.5 and 2.1.2.6.)

d. Validation and verification of the effects of soil overburden on seismic ground motion and wave propagation from bedrock, by direct measurement of motions and modeling of seismic waves as they pass the soil overburden (1988-1990). (Supports regulatory needs 2.1.2.1, 2.1.2.3, 2.1.2.5, and 2.1.2.6.)

3.2.4 Regulatory Application

The results from the program on the validation of dynamic effective stress models will be used by the staff to more accurately predict seismic liquefaction and settlement of nuclear power plant structures, systems, and components. The program on the effects of soil overburden on propagation of seismic waves from bedrock will better define deconvolution methods for determining the loads at foundation level and the spatial variation of the seismic loading in an earthquake. The studies on delayed stability failures at waterfront structures will improve the understanding of this phenomenon. The analytical/experimental information provided by the entire program, in summary, will be used to quantify the adequacy of the seismic design margins and provide improved confidence in the outcome of seismic PRAs. Standard review plans will be revised based on the results of the program and new regulatory guides developed.

3.3 Seismic Category I Structures Program (Appendix C)

3.3.1 Scope

This research will support improvements, reduce uncertainties, and aid in validating current seismic design criteria (2.6.3.1) by providing analytical methods and experimental data assessing how parameters used in the design of safety-related equipment and noncontainment structures are affected by earthquake loads. These parameters include fundamental frequency of the structure; damping values; and response spectra, accelerations, and displacements at

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various floor levels in the buildings. The sensitivity of these design parameters to changes in internal and external wall configuration; design practices; and magnitude, duration, and frequency content (2.6.3.2) of seismic input motion will be determined as the model configurations are subjected to quasi-static and seismic tests causing elastic and inelastic responses. These sensitivity tests are necessary because the auxiliary buildings, diesel generator buildings, etc., in the various nuclear power plants are very plant specific. In order to gain an insight into the effects of additional walls, different numbers of floors, or different size buildings, several parameters are varied so the results can be applied to the configurations that are actually in operating plants.

Failure data (mode and earthquake input level) will be obtained on all models tested, provided the static or seismic capacity of the facility is large enough. Even if complete failure, i.e., loss of load-carrying capability, does not occur, the building models will be subjected to loads significantly above equivalent Safe Shutdown Earthquake levels. Data from these tests will reduce the large uncertainties associated with the structural fragilities/capacities needed for seismic PRAs and seismic margin evaluations (2.2.3.2 and 2.2.3.3). These fragility/capacity data will also identify earthquake input levels where building performance is a major contributor to the seismic vulnerability of nuclear power plants (2.3.3.1 and 2.3.3.2).

Two tasks are being performed to help quantify the analytical-experimental differences in structural stiffness (2.4.3.1). First, quasi-static experiments will be performed on models fabricated with materials representative of those used in actual nuclear power plants. The majority of the earlier testing was done on models fabricated with microconcrete. Values of structural stiffness as a function of shear wall aspect ratio (wall height-to-length ratio), percentage of reinforcing steel, and input load magnitude will be obtained from the test data.

The second effort relates to analytical methods used to calculate structural stiffness. In cooperation with architect-engineering firms, various analytical assumptions will be employed and the results compared with earlier calculations. This effort will ensure that the analytical practices used are commensurate with those used by industry and not the cause of the analytical-experimental differences.

This research will also provide data to assess how shifts in structural frequency affect plant risk (2.4.3.2). Floor response spectra curves calculated using current design practices will be compared with those obtained from test data. Ideally, linear techniques can be developed to align the analytically/experimentally developed curves, thereby providing a correction factor that is a function of input acceleration level to be used in seismic margin evaluations. In addition, floor response spectra curves obtained from test data, in combination with simplified piping and system analytical models, will be used to assess how shifts in structural frequency affect plant risk. Simplified seismic PRA methods developed as part of the Seismic Safety Margin Research Program (SSMRP) or other seismic risk evaluation methods will be used to make this assessment.

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3.3.2 Integration and Relationship With Other Research

This program will provide structural frequency, damping, floor response spectra, and other related data on the behavior of buildings and building segments subjected to earthquake motions within and above the design basis. These data will be used by the Standard Problems for Structural Computer Codes Project (3.10) to establish benchmark-type standard problems to be used in computer code assessments; the Seismic Design Margins Program (3.13 and Appendix G) to aid in the development of guidelines for seismic margin evaluations; and the Structural Damping Project (3.6) to evaluate concrete damping values currently contained in regulatory guides and standard review plan sections. Information on the changes of floor response spectra that are used in the design of piping systems and components will be provided to the Piping Design Program (3.7) and the Seismic Component Fragility and Ruggedness Project (3.8 and Appendix D) for incorporation, as appropriate, in their analytical and experimental efforts. In addition, concrete cracking, spalling, etc., data will be provided to the Post-Earthquake Inspection Project (3.11) for inclusion in post-earthquake inspection and evaluation criteria.

A considerable amount of research has been performed on reinforced concrete shear walls. For example, Stanford University (Benjamin and Williams); Massachusetts Institute of Technology (Galletly and Antebi); Construction Technology Laboratories, a Division of Portland Cement Association (Bardla, Hanson, Corley, Oesterle, Fiorato, and Cardenas); and the University of Illinois (Sozen) have performed monotonic, quasi-static, or dynamic tests on models having different aspect ratios, reinforcing amounts and arrangements, and different boundary conditions. Information from these tests (e.g., model configuration, instrumentation, analytical-experimental comparisons, conclusions) have been used in program planning and, where applicable, in comparing results and conclusions.

The Japanese have carried out a number of experimental investigations related to nuclear power plant buildings. The main purpose of these investigations appears to be to develop design criteria and to show that structures do not fail at loads up to the design level. A technical information exchange agreement has been established with Japan (3.12 and Appendix F), and data from their tests will be evaluated to see if they support the analytical-experimental differences observed from this program's research.

3.3.3 Products

a. Experimental validation of the assumptions and analytical methods currently used by applicants and licensees to predict the fundamental frequency, accelerations, displacements, and floor response spectra of structures (1987-1989). (Supports regulatory needs 2.6.2.1 and 2.6.2.2.)

b. Failure mode and failure level data for various wall and floor arrangements contained in the concrete configurations tested (1987-1989). (Supports regulatory need 2.2.2.2.)

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c. The sensitivity of structural behavior (i.e., fundamental frequency; damping; and response spectra, acceleration, and displacements at various floor levels) to changes in internal and external wall configurations, and earthquake duration and magnitude beyond the initial design basis (1987-1989). (Supports regulatory needs 2.6.2.2, 2.2.2.1, and 2.3.2.)

d. An assessment of seismic risk associated with analytical-experimental differences in structural fundamental frequency calculations (1988-1989). (Supports regulatory need 2.4.2.)

3.3.4 Regulatory Application

The results from the program will be used to assess the need to change Regulatory Guides 1.61, "Damping Values for Seismic Design of Nuclear Power Plants," 1.92, "Combining Modal Responses and Spatial Components in Seismic Response Analysis," and 1.122, "Development of Floor Design Response Spectra for Seismic Design of Floor-Supported Equipment or Components." In addition, the analytical and experimental information delivered by this program will be used to help quantify seismic design margins, provide fragility data for probabilistic risk assessments, and aid in the treatment of external events in the implementation of the Severe Accident Policy Statement (SECY-86-162) (Ref. 15).

3.4 Containment Failure Modes Under Seismic Loads Project

3.4.1 Scope

Containment structures designed in accordance with Section III of the ASME Boiler and Pressure Vessel Code can be expected to perform adequately even if subjected to seismic loads far in excess of their design bases. The fundamental reason for this expectation is that the structures were proportioned and detailed so that they would respond elastically when subjected to the combined effects of a loss-of-coolant accident and the Safe Shutdown Earthquake. Although the effects of seismic loads and internal pressures differ, the net outcome of including the effects of both loadings is to significantly increase the capacity of the containment to withstand either loading when considered separately. In addition, the design criteria specified essentially elastic response. Since significant yielding must occur before the onset of failure, that aspect of design practice adds to the margin above design levels that can be expected in any containment.

Estimates of structural capacities for a number of containment shells have, indeed, indicated large expected margins in earthquake resistance. Two studies are especially worth noting. One (NUREG/CR-4334) (Ref. 19) summarized estimates of failure levels for concrete containments made in connection with seismic PRAs. The other (NUREG/CR-3127) (Ref. 20) focused on providing estimates of the resistance of steel containment shells that could be used in probabilistic evaluations. The plants studied were all located in the Eastern

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U.S. (i.e., east of the Rocky Mountains) in regions of low-to-moderate seismic activity and had Safe Shutdown Earthquakes ranging from 0.10g to 0.22g. The concrete containment study (Ref. 19) estimated median capacities ranging from 2.5g to 9.3g. The steel containment study (Ref. 20) provided mean estimates of capacity ranging from 1.45g to 16.25g. Considerable uncertainty is associated with these estimates. For example, in the concrete containment study, an attempt was made to include the effects of randomness and uncertainty and derive capacity estimates that were felt to have a high confidence of low probability of failure (HCPLF). The net result of reflecting the uncertainties in this way was to reduce the estimated capacities by a factor of about three with HCPLF estimates of shell capacity ranging from 0.8g to 2.7g. Notwithstanding the large uncertainties, it is still apparent that structural failure of the containment shell is not a significant potential failure mode under earthquake loading.

It is more likely that, for soil sites, any containment failure would be associated with a foundation failure, leading to failure of piping. This potential failure mode has not been studied extensively. But, in one case where it has been considered, it has been found to be dominant. In the previously cited review of seismic PRA studies (Ref. 19), the median estimates for failure of a containment structure and for soil failure beneath its foundation slab were 2.9g and 0.9g, respectively. When uncertainties were factored into the estimating procedure, HCPLF estimates were 0.8g and 0.3g, respectively.

The fundamental question is: Will containment performance in a severe accident be significantly degraded if the accident were initiated by a large earthquake? A soil failure would amplify motions at piping penetrations and could create a leak path. Another possible failure mode is local damage at operable penetrations that might reduce pressure-retaining capability.

Research on containment failure modes under seismic loads will be carried out during FY 1986-1988 with the intention of assessing the ability of analytical methods to predict behavior near failure. It is important to remember that containment design technology has focused on assurance of performance under design conditions--not margins to failure. The first effort, currently in progress, is a detailed examination of six plants (three PWRs, three BWRs) to identify possible failure modes under large seismic loads. The extent to which predictions of failure at the most likely locations rest on calculations that have been verified by experiment is of particular significance. There is a distinct possibility that, notwithstanding the wide differences in details for existing containment designs, it will be possible to show with confidence that implausible earthquake levels would be required to cause failure at most locations. But it is also likely that, for some designs, some failure modes will be predicted at levels of interest. Necessary experiments will be identified and planned during FY 1987-1989 and carried out in FY 1988 and 1989. It is likely that the outcome of this research will, in the context of PRAs, improve confidence in mean or median estimates of failure level.

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Resolution of this fundamental question is necessary in order to permit more realistic treatment of containment behavior for externally initiated accident scenarios in probabilistic risk assessments of nuclear power plants (2.3.3.1).

3.4.2 Integration and Relationship With Other Research

Based on the initial studies cited above, indications are strong that the dominant failure mode for soil sites will be related to rigid body displacement resulting from large soil motions. Consequently, there will be a strong coupling between this research and the work, outlined in Section 3.2 and Appendix B to this plan, on soil response. Additional information likely to be used will come from the experiment on a model containment structure embedded in a soft seismically active site in Taiwan, described in Section 3.9 and Appendix E to this plan. While the purpose of that experiment is to validate calculations of soil-structure-interaction effects, it is possible that large motions will be recorded over the 5-year life of the experiment.

There is also interest in foreign countries in the behavior of containments under larger-than-design-basis earthquakes. Work is in progress in the Federal Republic of Germany that is focused on spherical steel containments. While the results will not be directly applicable to U.S. designs, insights into failure modes and the credibility of predictive methods will be of interest. In the United Kingdom, there is an ongoing effort related to the Sizewell B design. This containment has great similarity to many prestressed concrete designs in the U.S., and results are more likely to be directly applicable. A new program, emphasizing the use of recorded earthquake data at the decommissioned Carorso plant, is being formulated in Italy. The extent to which this effort will focus on containment performance is not clear at this time. But, given the significance of the problem and the Italian practice of using reinforced concrete containment designs, there are good prospects for information developing from that program. Finally, there are ongoing efforts to develop cooperative programs on containment performance with Japan. That activity is described in Section 3.12 and Appendix F to this plan.

3.4.3 Products

a. Research on containment failure modes under seismic loads, started in FY 1986, will be completed in FY 1987. The purpose of this effort is to assess the ability of analytical methods to predict failure modes of the different types of containment designs. (Supports regulatory need 2.2.2.2.)

b. Necessary experiments will be identified and planned during FY 1987 and carried out in FY 1988-1989. It is likely that, in the context of PRAs, the outcome of this research will be to improve confidence in estimates of mean or median failure levels. (Supports regulatory need 2.3.2.)

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3.4.4 Regulatory Application

The principal application of this research will be in the implementation of the Severe Accident Policy Statement (SECY-86-162).

3.5 Dams and Embankments Project

3.5.1 Scope

The objective of this program is to provide analytical and experimental data to validate current methods of analysis used to predict the safety and dynamic response of dams and embankments used in the storage of coolant water for nuclear power plants (2.6.3.2). Knowledge of the dynamic response of dams and embankments is important to plant safety because coolant system components are often mounted on a dam or embankment. The adequacy of the methods of analysis for dams and embankments is especially important in light of the question whether existing plant safety components will perform their safety functions when subjected to earthquakes greater than those considered in the design of the plant (2.6.3.2 and 2.2.3.1).

From the information and data to be assembled in this program, improvements in the methods of analyzing dams and embankments will be recommended. Information on the interaction of base soil and the dam or embankment will be developed. This research will reduce existing uncertainties in the response analysis of dams and embankments, particularly when they are subjected to dynamic load conditions close to their point of failure.

Initially valuable analytical and experimental data will be collected, reviewed, and analyzed with respect to the objectives of this program. If necessary information and data to evaluate the existing methods of analysis of dams and embankments are not available, an experimental program will be developed and performed to obtain this information.

3.5.2 Integration and Relationship With Other Research

This program will assemble and develop information and data related to the structural frequency response spectra and failure of dams and embankments typically used in conjunction with nuclear power plants when subjected to seismic events. The information will be used to develop benchmark-type standard problems for assessing the validity of the analytic methods used to predict the response and safety of dams and embankments. Data and information related to soil-structure interaction developed in the Standard Problems for Structural Computer Codes Project (3.10) will be considered.

Information and data developed in past NRC research projects will also be considered; i.e., work performed at the University of British Columbia and Cambridge University. Also, information gained in the soil response research program (3.2 and Appendix B) will be considered.

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Interrelationship with present and future NRC research projects will be established, particularly with those dealing with response of the ground at a distance from epicenters. The soil-structure-interaction approach may be used as well for the case of dams of relatively large size and weight. Damping problems will also be considered and related to these projects if appropriate.

3.5.3 Product

This program will begin in FY 1988. In that year data and information assembled will be developed into a set of benchmark problems to evaluate existing methods of dam and embankment safety and dynamic response analysis. (Supports regulatory needs 2.6.2.1, 2.6.2.2, and 2.2.2.1.) If necessary information and data do not exist for specific ranges of design or loads, parameters for an experimental research plan will be developed in FY 1989 to generate this information and data. It is anticipated that this program will end in FY 1991 with an appropriate set of benchmark problems and recommendations to improve existing methods of dynamic response and failure analysis, especially near the point of dam and embankment failure.

3.5.4 Regulatory Application

The benchmark standard problems will be used by the NRC to evaluate the methods used to predict the safety and response of dams and embankments in new nuclear power plants and to judge the adequacy of existing dams and embankments subjected to seismic loads greater than those used in the design.

Recommendations for the improvement in analytical methods will be incorporated in these methods or new methods developed.

3.6 Structural Damping Project

3.6.1 Scope

The values of the structural damping coefficients provided in Regulatory Guide 1.61 were established from experimental and structural service data generated over 15 years ago. These values were developed for structures that respond elastically to a dynamic environment. During the past 15 years many experiments have been conducted. The data recorded from these experiments can provide a clear insight into the damping characteristics of structures. There is a need to evaluate these data and determine if structural damping coefficients should be modified to improve the results of analytical methods to predict the response of structures (2.6.3.1).

The NRC is concerned with the potential response of nuclear power plants subjected to seismic events larger than they were designed for. It is possible that these larger seismic events will excite the plant structures into the nonlinear and inelastic regions. If such is the case, analytical methods must be capable of predicting this response (2.2.3.1, 2.6.3.2). To accomplish this,

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techniques must be developed to treat the nonlinear damping of structures. Damping coefficients for nonlinear response must be defined, and these coefficients must be determined.

It will also be the objective of this program to survey the nonlinear phenomena of structural response and define nonlinear damping coefficients and then review available experimental and service data to establish the coefficients. It may be necessary to plan an experimental program to develop appropriate data where none now exists.

3.6.2 Integration and Relationship With Other Research

An agreement is being established between the NRC and the Japanese Agency of Natural Resources and Energy to exchange seismic research information (3.12 and Appendix F). It is anticipated that information and data on the dynamic response and damping will be received from Japan as part of these exchanges. Also, experimental data and analyses obtained from the Seismic Category I Structures Program (3.3 and Appendix C) will be used to evaluate damping values for concrete.

The damping values obtained from the above two programs, Japanese Exchange Program and Seismic Category I Structures Program, will be analyzed, compared to existing damping data, and verified by experiments of this program. Concluding information on damping coefficients will be included in regulatory guides. This program will provide damping data for possible use in other NRC research programs.

The Seismic Category I Structures Program being conducted at the Los Alamos National Laboratory for the NRC is generating experimental data on structural models subjected to static and seismic loads. It is anticipated that the reduction of the resultant experimental data will generate both linear and nonlinear insights into structural damping that will be useful in this program.

Other sources of structural response data now available and now being generated both in this country and in foreign nations will be sought, reviewed, and, where appropriate, used to improve our insight into structural damping, both in the linear and nonlinear response modes.

3.6.3 Product

An update on linear structural damping coefficients, an appropriate analytical definition of the nonlinear damping of structures, and appropriate nonlinear damping coefficients. (Supports regulatory needs 2.6.2.1, 2.2.2.1, and 2.2.2.2.) In addition, new knowledge on the dynamic response of structures gained in the information search part of this program will be collected and analyzed as part of the Seismic Category I Structures Program (3.3 and Appendix C) and Containment Integrity Research Program (Ref. 21).

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3.6.4 Regulation Application

The results of this program will be used to update Regulatory Guide 1.61, "Damping Values for Seismic Design of Nuclear Power Plants." The regulatory staff will be in a position to use these updated values to judge the safe seismic response of nuclear plant structures.

3.7 Piping Design Program (NUREG-1222)

NRC-sponsored research to confirm or improve the adequacy of current piping dynamic load design criteria is an integral part of the Piping Research Program Plan (NUREG-1222) (Ref. 22). A brief discussion of the scope, products, and regulatory application of this research will be given in this plan because of the strong interrelationship between piping dynamic load design and the overall seismic design of nuclear power plants.

3.7.1 Scope

The chief objectives of piping design research are to provide the bases for evaluating current design criteria and for developing and justifying changes to these criteria that should lead to more balanced and safer design. This is to be done by better defining the response and failure behavior from various loadings (particularly dynamic loads) and by making integrated assessments of how these loadings and their associated design criteria affect the overall reliability of piping systems. The scope of the piping research discussed below is directed primarily toward those research needs identified by the USNRC Piping Review Committee in Volumes 2 and 4 of NUREG-1061 (Ref. 23). These deal with design criteria for seismic and other dynamic loadings. New research items have also been added to address needs discovered upon implementation of standards activities recommended by the Piping Review Committee and upon completion of recent research studies.

The NRC is cooperating with the EPRI in the Piping and Fitting Dynamic Reliability Program. The objectives of this program are to identify failure mechanisms and failure levels of piping components and systems under dynamic loadings, to provide a data base that will improve our prediction of piping system response and failure due to high-level dynamic loads, and to develop an improved, realistic, and defensible set of piping design rules for inclusion in the ASME Code (2.5.3.2).

Forty piping component tests are being conducted at ANCO Engineers. These will be completed in late 1987, with the NRC and EPRI each funding 20 tests. The objective is to systematically obtain dynamic failure data for components under severe (but characteristic) seismic and high-frequency loadings. Elbows, tees, reducers, support connections, nozzles, and lugs are being tested. The ANCO tests completed to date show that ratchetting and fatigue (not cross-sectional collapse) are the predominant failure modes and that failure levels are much higher than previously believed. In 1987 through 1988, the Energy

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Technology Engineering Center (ETEC) will conduct dynamic failure tests of 6" carbon steel and stainless steel piping systems. These systems will be composed of components similar to those tested in the ANCO tests. They will be first shaken at design levels to provide benchmark response information for both synchronous and nonsynchronous support input loadings; then they will be tested at much higher levels that are estimated to cause dynamic inertial failures.

The EPRI/NRC Piping and Fitting Dynamic Reliability Program began in the spring of 1985 and will end in 1988. The NRC's contributions to this effort have been chiefly through the funding of the tests discussed above. EPRI will fund other component and systems tests and will also conduct specialized fatigue ratchet tests at General Electric in Schenectady. EPRI funds General Electric in San Jose to manage the overall program and provide analytical support.

The NRC Piping Review Committee made a recommendation to develop simple estimation methods for inelastic piping dynamic response (2.5.3.2). This is needed both to better quantify piping seismic design margins and to help accommodate in the design process the potential impact of higher dynamic stress criteria that could result from the EPRI/NRC program discussed above. The NRC is sponsoring investigations in this area by both the Hanford Engineering Development Laboratory (HEDL) and Structural Analysis Technologies. Evaluations and recommendations by both organizations will be completed in 1987.

Studies have shown that when new criterion changes such as higher damping are made to lessen the overconservatisms in piping inertial load design, the current load criteria for both nozzles and supports become limiting. Since 1985, the Oak Ridge National Laboratory has been investigating ways to better evaluate the dynamic load behavior of piping nozzles and branch connections (2.5.3.3). In 1987, Oak Ridge will complete its review and evaluation of flexibility analysis methods for branch connections and vessel nozzles. Improved flexibility factor design guidance in the form of analytical formulas and/or design graphs as well as proposed ASME Code rule revisions will be developed. The final results will be documented in a report in 1988.

The Idaho National Engineering Laboratory (INEL) Pipe Damping Study has been the major research contributor to date in the area of pipe damping (2.5.3.2). INEL testing and data evaluation have supported the development and acceptance of Code Case N-411 and have provided new information on high-frequency and high-level pipe damping. Recently, the ASME Task Group on Pipe Damping, with research support from EPRI, began a new effort to improve pipe damping criteria and to better address their analytical application. It is hoped that a revision of Regulatory Guide 1.61 can begin when the ASME Task Group completes its current task. In 1987, with NRC funding, INEL will provide consulting support to the ASME/EPRI effort. In 1987 and 1988, there will likely be other tasks the INEL will need to perform to address technical and licensing questions about the new ASME criteria before they can be endorsed by the NRC.

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Brookhaven National Laboratory's Combinational Procedures for Piping Spectra Analysis Program was initiated in 1985 to investigate a number of new spectra methods identified by the NRC Piping Review Committee. In 1985 and 1986, this program will conduct studies to evaluate several proposed methods for more appropriately accounting for the effects of closely spaced modes and high-frequency modes (2.5.3.1).

The evaluation and acceptance of recently proposed changes in dynamic piping design criteria have been done largely on an item-by-item basis. The NRC licensing staff, however, is continually faced with applications that intend to use combinations of new criterion changes and needs a basis for evaluating the effect of these proposed combinations (2.5.3.1). (Of particular concern is the use of Code Case N-411 with any other proposed criterion change.) A research project will be developed in 1987 to systematically evaluate the cumulative effect of proposed piping criterion changes. A key element of this project will be the use of physical test data along with analytical benchmarks to serve as "baseline" cases for comparing the response margins of various response techniques.

A research project to be developed in 1987 and implemented in 1988 will deal with the evaluation of pipe support criteria in light of suggested changes to piping design criteria and in response to needs identified in an ongoing Pressure Vessel Research Committee assessment of piping support design (2.5.3.4). Another new project to begin in 1988 will make systematic evaluations of piping earthquake experience data to assess current and new design criteria for piping system design (2.5.3.2).

3.7.2 Integration and Relationship With Other Research

While research on seismology, soil-structure interaction, and building response is being performed under other programs, the piping research programs will need to address relevant issues that these studies discover. For example, the Seismic Category I Structures Program has conducted shear wall tests that indicate that wall stiffnesses and input load spectra frequencies may be much lower than now considered in design. If this holds true, the impact on current piping design needs to be generically evaluated.

Seismological research that would support the "decoupling" of the Operating Basis Earthquake definition from being one-half of the Safe Shutdown Earthquake will have a big impact on piping design. This was a recommendation of the NRC Piping Review Committee. The NRC is developing plans to revise Appendix A to 10 CFR Part 100. This may be a broader effort than what was recommended by the Piping Review Committee and probably will not be completed until at least 1991. If this action does indeed go forward, it now seems that the end product will be a "forward looking" regulation and thus further research would be needed to support changes to the piping designs of already licensed plants.

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As piping response test data are obtained from programs outside the scope of the piping research program, these will be evaluated and used by the latter. "Targets of opportunity" will come from the HDR and Tadotsu pipe tests under the Validation of Seismic Calculational Methods Program.

In the past few years, NRC piping research has been coordinated with related work sponsored by EPRI. This relationship will continue in the future and information will be exchanged for independent projects as well, of course, as for the Cooperative EPRI/NRC Piping and Fitting Dynamic Reliability Program.

3.7.3 Products

a. By the end of 1987, a total of 40 pipe components will be dynamically tested to failure at ANCO (under joint EPRI and NRC funding). (Supports regulatory need 2.5.2.1.)

b. Both carbon steel and stainless steel 6" piping systems will be dynamically tested to failure at ETEC in FY 1987-1988. Before failure levels are input, a series of design level response tests will be run to serve as "baseline" benchmarks for future licensing decisionmaking. (Supports regulatory need 2.5.2.1.)

c. The NRC will sponsor INEL in a support role for the new ASME/EPRI pipe damping effort in FY 1987. (Supports regulatory needs 2.5.2.1 and 2.5.2.3.)

d. Oak Ridge National Laboratory will provide improved guidance on nozzle and branch connection flexibility evaluation and design in FY 1987-1988. (Supports regulatory need 2.5.2.2.)

e. Both HEDL and Structural Analysis Technologies will evaluate simplified nonlinear piping response prediction methods in FY 1987. (Supports regulatory need 2.5.2.1.)

f. Brookhaven National Laboratory will complete its evaluation of spectrum methods considering independent support motion, closely spaced modes, and high-frequency modal combination in FY 1987. (Supports regulatory need 2.5.2.3.)

g. Evaluations leading to improved piping support design criteria will be made in FY 1988-1989. (Supports regulatory need 2.5.2.2.)

h. An assessment of the adequacy of currently proposed energy-absorbing support techniques will be made in either late FY 1987 or in FY 1988. (Supports regulatory need 2.5.2.2.)

i. Systematic evaluation of the cumulative effect of proposed piping criterion changes will be made in FY 1987-1989. (Supports regulatory need 2.5.2.3.)

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j. Dynamic event experience data for piping will be systematically evaluated in FY 1987-1989. (Supports regulatory need 2.5.2.1.)

3.7.4 Regulatory Application

The EPRI/NRC Piping and Fitting Dynamic Reliability Program will lead to major revisions to the parts of ASME Code Section III, Subsections NB/NC/ND 3600, that specify design rules for dynamic inertial loads.

The Oak Ridge National Laboratory study on nozzle and branch connection design rules and flexibility estimation methods will lead to changes to the industry standards and possibly the standard review plan.

ASME Code Section III, Subsection NF, will be revised to incorporate improvements resulting from NRC-sponsored research on piping supports.

Regulatory Guide 1.61 will be revised (part of Generic Issue 119) to incorporate changes in pipe damping criteria resulting from NRC- and EPRI-sponsored research.

Section 3.6.2 of the standard review plan will be revised to incorporate improvements in piping response spectrum methods resulting from NRC-sponsored research.

3.8 Seismic Component Fragility and Ruggedness Project (Appendix D)

3.8.1 Scope

This effort assembles, catalogs, and interprets existing seismic fragility information on electrical and mechanical components important to safety (2.2.3.2). The emphasis is on electrical components such as motor control centers, switchgear, and relays. The aim is to provide a reliable experimental basis for gaging failure levels and modes under seismic excitations and therefore could lead to enhanced credibility of seismic PRAs and margin studies.

An important aspect of the investigations is testing the hypothesis that electrical and mechanical components have higher failure levels than those presently assumed in seismic PRAs and, as a consequence, that the significance of the earthquake threat may be diminished in licensing decision-making. This research will contribute to the development of simplified seismic risk methodologies by eliminating certain branches on event trees and fault trees that do not contribute to risk (2.2.3.3). These branches can be identified when the actual component fragilities are shown to be extremely large in comparison with predicted seismic responses. Realistic component fragilities are a prerequisite to validation of current seismic PRA methods.

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3.8.2 Integration and Relationship With Other Research

Results from this program have supported the resolution of Unresolved Safety Issue (USI) A-46. Specifically, the contractor (Brookhaven) was able to determine electrical cabinet damping values and amplification factors experimentally at the request of NRR personnel involved in resolving USI A-46, which permitted rational decisionmaking and evaluation otherwise impossible. Two letter reports (Refs. 24 and 25) transmitted this information to NRR and the Senior Seismic Review and Advisory Panel. Contractual sources of experimental data used in this program are Westinghouse, General Electric, Combustion Engineering, Brown Boveri, Telemecanique, and United Control. Additionally, through a cooperative agreement with EPRI, free access to seismic fragility data acquired by the EPRI contractor, ANCO Engineers, has been achieved.

Major aspects of the interpretation of prior tests involve correlation of results from different test techniques (sine burst versus sine sweep versus multifrequency tests and single axis versus multiaxis tests) and the development of a single parameter description of fragility. This latter will be developed with the assistance of an advisory panel and consultants. This work extends previous work undertaken by Lawrence Livermore National Laboratory under the Seismic Safety Margins Research Program (SSMRP), which was based largely on judgment, analysis, and limited military test data. It is believed that this is the first comprehensive attempt to assemble and evaluate the entire experimental seismic fragility data base of existing data. Requests have been received from Japan, France, and the United Kingdom for the results of our studies. However, we are depending entirely on domestic sources of information at this time.

3.8.3 Products

a. Single parameter fragility descriptors for some 27 different equipment categories. (Supports regulatory need 2.2.2.2.)

b. Limited information on how anchorage and cabinet stiffness affect fragility estimates. (Supports regulatory need 2.2.2.2.)

c. A computerized seismic fragility data bank. (Supports regulatory need 2.2.2.2.)

NUREG/CR-4659 (Ref. 26) was published in June 1986 giving fragility information on motor control centers and switchgears. Additional reports are expected in the summer of 1987 and the summer of 1988.

3.8.4 Regulatory Application

No standard review plan sections, regulatory guides, or other NRC regulatory documents are affected by this program. This work would be useful only for seismic PRAs and margin studies. Investigations of the importance of specific electrical and mechanical components or generic classes of

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components as they contribute to the seismically induced release of radioactivity become more realistic when seismic fragilities are experimentally defined. In more general terms, the importance of earthquakes themselves in comparison with other design basis events is more clearly defined as a consequence of these studies.

3.9 Validation of Seismic Calculational Methods Program (Appendix E)

3.9.1 Scope

Seismic PRA methods have been applied to clarify safety issues for nuclear power plants since seismic events can simultaneously affect many plant systems and therefore can be a significant or even dominant contributor to overall risk. The randomness of the seismic hazard, the uncertainties and variabilities of fragility and response data, and the approximate nature of the methodology raise questions of credibility with respect to the results of seismic PRAs and subsequent regulatory actions. While the ultimate answer to these questions depends on the intended use of seismic PRAs, it is nevertheless necessary to validate the methodologies so they may be used with confidence and credibility in the regulatory decision process. The predictive methods to be validated are used in both probabilistic and deterministic predictions. The purpose of validation research is to obtain information that can be used by NRC to develop acceptance criteria for predicting the behavior of nuclear power plants subjected to large earthquakes and thus improve the regulatory process. This activity is intended to support research objectives on evaluating the adequacy of current criteria and methods (2.6.3.1), assessing the risk from earthquakes larger than the design basis (2.2.3.1), and determining seismic vulnerabilities (2.3.3.1).

The fundamental strategy is to engage in cooperative research programs in order to maximize available resources. Three efforts have been developed:

a. Participation in a soil-structure-interaction experiment being performed near Lotung, Taiwan, by EPRI.

b. Participation in the Phase II experiments being performed at the Heissdampfreaktor (HDR) facility in Kahl, Federal Republic of Germany, by Kernforschungszentrum Karlsruhe (KfK).

c. Participation in tests to be performed on the large shaker table in Tadotsu, Japan, by the Nuclear Power Engineering Test Center (NUPEC).

Summaries of these activities are provided below.

a. EPRI Cooperation

Argonne National Laboratory is the NRC coordinator for this effort. EPRI has constructed, in a seismically active area in Taiwan, a model about one-

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fourth the size of a concrete containment. The Taipower Company has provided the site and managed the model construction. EPRI has also installed instruments in the model and in vertical and horizontal arrays in the vicinity of the model and will record earthquake responses over a 5-year period. NRC has performed low-level vibratory tests of the model to provide baseline data on modal parameters. Future NRC effort will be in providing analytical models to predict soil-structure-interaction effects for the recorded earthquakes and in comparing predictions with observations.

b. HDR Cooperation

Argonne National Laboratory is also the NRC coordinator for this effort. The HDR facility is a modification of a superheated steam reactor that was decommissioned and modified for research in 1973. A series of experiments (called Phase I tests) was conducted from 1975 to 1983 involving experiments on materials engineering, thermal hydraulics, and mechanical and earthquake engineering. The primary focus of the experiments is to compare predictions by analytical models with experiments. The Phase II experiments from 1984 to 1988 are similarly motivated and will examine higher levels of response where damage to structures, systems, and components is expected. NRC participation in the seismic tests will involve providing predictions for the response of structures and piping systems excited by shakers. One series of experiments in which the containment building was excited by a large shaker was conducted in June-July 1986. This series of experiments was designated (based on a German acronym) the SHAG tests.

In the SHAG experiments, a very large eccentric-mass coastdown shaker, designed by ANCO Engineers, capable of developing a force in excess of 1,000 tons was mounted on the operating floor of the HDR building. The shaker was brought up to the desired starting speed (1.2-8.0 Hz) with its two arms in a balanced condition. Unbalancing takes place after the arms are decoupled from the drive system. Firing an explosive bolt releases the movable arm, which swings around and couples with the fixed arm, forming a large eccentric mass that provides a variable (both in magnitude and direction) force during coastdown through the building resonances. The SHAG tests were designed to provide the maximum possible loading for the HDR building, equipment, and piping without global structure-soil failure. The actual SHAG test series consisted of 25 runs with starting frequencies at 8.0 Hz (9 runs), 6.0 Hz (5 runs), 5.6 Hz (1 run), 4.5 Hz (6 runs), 2.1 Hz (1 run), and 1.6 Hz (3 runs). Only the 8.0 and 5.6 Hz tests were at full load, (10^4 kN), the 6.0 Hz tests were at about 90 percent of full load, while all the others were performed with the VKL (experimental piping loop) piping in hot conditions. Nevertheless, peak accelerations and displacements in the building were quite substantial and nonlinear behavior of the soil-structure system was clearly observed. Much local damage, such as concrete cracking and interior masonry wall collapse, occurred. During the rocking experiments (1.6 Hz), much energy was transferred to the soil as evidenced by high acceleration, cracking, and subsidence. Also,

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impact occurred between the HDR building and the equipment tower and the connecting bridge to the office building. Strains in the HDR shield building wall approached or exceeded their estimated limit values.

Most importantly, the tests of the VKL piping system with various hanger configurations, which were of primary interest to NRC, were in general successful and should provide much useful information. Similarly, the goals of the gate valve qualification effort were in general achieved.

A series of experiments in which high-level loads will be applied to the VKL piping system by servo-hydraulic actuators is planned for the fall of 1987. These tests will be designed to excite the piping well into the inelastic range. Response of the gate valve will also be monitored during this series of experiments, known as the SHAM tests.

c. NUPEC Cooperation

Brookhaven National Laboratory is the NRC coordinator for this effort. A massive testing effort was started in 1974 under the sponsorship of the Japanese Ministry for International Trade and Industry. The Nuclear Power Engineering Test Center was established and the largest shake table facility in the world was constructed at the Tadotsu Engineering Laboratory. The table is 15m x 15m with a capacity of 1,000 tons. (For purposes of comparison, the largest shake table in the U.S., operated by the Richmond Field Station of the University of California, is 6m x 6m with a capacity of 60 tons.) The test series, from 1982 to 1988, will involve eight specimens representing containment vessels, primary loops, reactor pressure vessels, and reactor internals for both PWRs and BWRs. All specimens will be excited with time histories representative of the Japanese design earthquakes, designated S_1 and S_2 and similar in intent to our Operating Basis Earthquake and Safe Shutdown Earthquake. Responses to those motions will be monitored. The series is known officially as the Seismic Proving Test Programme. The total cost of the Japanese program exceeds $500M, including about $250M for the test facility.

NRC's main interest lies in determining the ability of analytical methods to predict the onset of component damage under very large earthquake motions. To that end, we have negotiated for tests to be performed after the "proving tests" have been completed on a 1/2.3 model of a PWR piping loop. The tests in which NRC will cooperate will involve increasing the excitation within the limits of the table and modifying the specimen to induce inelastic response. Those experiments will be performed in the spring of 1988.

3.9.2 Integration and Relationship With Other Research

The cooperative research program with EPRI will yield data that will be useful in other research programs described in this plan. While the experiment is focused on soil-structure-interaction effects, the data collected will include ground-motion records from both horizontal and vertical arrays near the

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model structure. These records are of potential use in the research on Soil Response, described in Section 3.2 and Appendix B to this plan. Also, data from structural response measurements at different locations in the structure will be of use in the Structural Damping Project, described in Section 3.6 of this plan.

Results from the HDR testing effort can be used as input to the Piping Design Program, described in Section 3.7 of this plan. Also, work performed in the Federal Republic of Germany on the soil motions generated by the large shaker experiment will be available to the NRC and may be of use in the Soil Response Program (3.2 and Appendix B).

Results from the cooperative effort with NUPEC will be of use to the Piping Design Program (3.7). Also, through interaction with the Exchange of Seismic Research Information Project effort, described in Section 3.12 of this plan, existing data will be sought that is suitable for validation research.

3.9.3 Products

a. Comparisons of predictions of piping response with measurements taken at the HDR facility during the large shaker tests (1987). (Supports regulatory needs 2.6.2.1 and 2.2.2.1.)

b. Comparisons of measurements made during the high-level shaking tests to be performed at the HDR facility in 1987, with predictions of damage mechanisms in piping systems (1988). (Supports regulatory needs 2.6.2.1, 2.2.2.1, and 2.3.2.)

c. Comparisons of predictions of soil-structure-interaction effects made using representative methods with measurements from a large earthquake recorded at the site in Lotung, Taiwan (1987). (Supports regulatory needs 2.6.2.1 and 2.2.2.1.)

d. Comparisons of soil-structure-interaction effects for a number of earthquakes recorded at the site in Lotung, Taiwan (1989). (Supports regulatory needs 2.6.2.1 and 2.2.2.1.)

e. Comparisons of predictions of elastic and inelastic response with measurements recorded at the NUPEC shake table experiment (1989). (Supports regulatory needs 2.6.2.1 and 2.2.2.1.)

3.9.4 Regulatory Application

The analytical and experimental information delivered by this program will be used to help quantify seismic design margins, provide response data for probabilistic risk assessments, and aid in the treatment of external events in the implementation of the Severe Accident Policy Statement (SECY-86-162).

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3.10 Standard Problems for Structural Computer Codes Project

3.10.1 Scope

The intent of this research program is to address the issue of the adequacy of current design criteria and seismic analyses methods (2.6.3.1).

The objective of this research is to develop standard problems with experimentally known solutions (benchmarks) for use by the licensing staff to validate methods used by licensee and applicant to calculate the seismic response of nuclear power plant structures.

To accomplish the objective of the program, the research contractor will determine the parametric range of application required of most common analytical methods currently used to predict the behavior of nuclear safety-related structures under accidental and extreme environmental loadings, including soil-structure-interaction effects associated with seismic loadings. After the review is completed and ranges of application are established, benchmark problems will be developed based on experimental and actual service data to be used to demonstrate the adequacy of analytical models used to represent the behavior of safety-related structures in these ranges of application.

3.10.2 Integration and Relationship With Other Research

Presently, there is a need for additional data to address most of the uncertainties related to soil-structure-interaction analysis, including data from actual power plants subjected to earthquakes and instrumented in the free field. Some of this information will be obtained through information exchange programs (3.12 and Appendix F). Also, to validate methods that are used to predict the response characteristics of nuclear power plant structures subjected to seismic loads (including those loads greater than design), additional inservice and experimental data are needed. Some of this information will be obtained from the Seismic Category I Structures Project (3.3 and Appendix C).

Pertinent research performed by others include EPRI research in the soil-structure-interaction area on structural models excited by simulated earthquakes. Simulation techniques include explosive-induced ground motion and forced vibration (shaker) ground-motion tests (e.g., Simquake). EPRI with cooperation from the NRC has also joined Taipower in an effort to measure and record soil-structure-interaction characteristics on structural models subjected to actual earthquakes at a site near Lotung, Taiwan (3.9 and Appendix E).

3.10.3 Products

a. Investigation of ground-water effects on the response of Category I structures (variation of ground-water depth) (1987). (Supports regulatory need 2.6.2.1.)

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b. Develop benchmark problems to investigate the adequacy of structural models used currently to perform safety evaluations of nuclear Category I structures (1988). (Supports regulatory need 2.6.2.1.)

c. Evaluation of new data with the aim of improving benchmarks (1989). (Supports regulatory need 2.6.2.1.)

3.10.4 Regulatory Application

The data collected and insights gained in this program were used by the Office of Nuclear Reactor Regulation (NRR) to evaluate the structural and soil response of the Diablo Canyon power plant review in FY 1984. Through this program, a workshop was held to discuss the state of the art in soil-structure-interaction analyses. The information presented and summaries prepared by the moderators at each of the soil-structure-interaction workshop sessions are serving as bases for resolution of Unresolved Safety Issue A-40, "Seismic Design Criteria." This resolution will result in changes to Sections 3.7.1 and 3.7.2 of the standard review plan.

3.11 Post-Earthquake Inspection Project

3.11.1 Scope

This research is focused on developing procedures to evaluate the operability of a nuclear power plant following an earthquake (2.6.3.3). Criteria have been developed (Regulatory Guide 1.12) relative to the location, characteristics, and maintenance of seismic instrumentation. These instruments will provide information on the vibratory ground motion and resultant vibratory response of representative Category I structures and equipment. However, guidance on how these data should be treated, i.e., retrieved, processed, and evaluated, has not been provided. This research will evaluate criteria prepared by the American Nuclear Society Working Group and recommend acceptance or propose alternative criteria. In conjunction with data evaluation, guidance defining exceedance of the Operating Basis Earthquake at a nuclear power plant, thereby requiring shutdown of that plant (10 CFR Part 100, Appendix A, V(a)(2)), will be provided.

This research will also lead to inspection procedures and acceptance criteria relative to post-earthquake evaluations. If a power plant facility is shut down after an earthquake, considerable review and evaluation will be required prior to restart. For example, soil foundations need to be inspected for signs of soil failure (slides, fissures, liquefaction) that may affect structure, system, and component safety. Acceptable limits on settlement, etc., will be defined. Procedures to inspect structural components (concrete walls/slabs, steel framing) for signs of damage such as cracking and spalling of concrete and yielding of steel beams will be developed. Acceptance criteria relative to how much cracking or bending is acceptable before replacement is recommended will be developed. Mechanical systems critical for safe operation

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need to be inspected for leaks, pipe support failures, and equipment anchorage failures. Cable trays, instrumentation panels, etc., need to be inspected for damage. Procedures will be developed to determine which equipment needs to be inspected and acceptance criteria established, e.g., do bent cable trays need replacement?

3.11.2 Integration and Relationship With Other Research

This program will make use of data from other NRC research programs to develop inspection and acceptance criteria for post-earthquake evaluations--in particular, concrete cracking, spalling, etc., information from the Seismic Category I Structures Program (3.3 and Appendix C); pipe support failure, leakage, etc., information from the Piping Design Program (3.7); equipment anchorage failures, etc., data from the Seismic Component Fragility and Ruggedness Project (3.8 and Appendix D); and data on structures and equipment performance during tests in an actual nuclear power plant (HDR) from the Validation of Seismic Calculational Methods Program (3.9 and Appendix E). In addition, actual earthquake experience data and ongoing studies by the Seismic Qualification Utilities Group (SQUG) will be used to establish limit states and acceptance criteria of buildings and equipment.

Standards developed by the American Nuclear Society (ANS) Working Group 2.2 on seismic instrumentation and Working Group 2.10 on handling data from seismic instruments will serve as the starting basis for regulatory guide development. Coordination with EPRI and ANS Working Group 2.23 relative to the development of a national standard on post-earthquake evaluation will be established.

3.11.3 Products

a. Procedures to assess the extent of earthquake-induced damage to mechanical and structural systems enabling the staff to make decisions on plant degradation and operation (1991). (Supports regulatory need 2.6.2.3.)

b. Evaluation of ANSI/ANS-2.2-1987, "Earthquake Instrumentation Criteria for Nuclear Power Plants," and ANSI/ANS-2.10-1988, "Guidelines for Retrieval, Review, Processing, and Evaluation of Records Obtained from Seismic Instrumentation," for endorsement by current or new regulatory guides (1988). (Supports regulatory need 2.6.2.3.)

3.11.4 Regulatory Application

a. Revise Regulatory Guide 1.12, "Nuclear Power Plant Instrumentation for Earthquakes," to endorse ANSI/ANS-2.2-1987, "Earthquake Instrumentation Criteria for Nuclear Power Plants."

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b. Develop new regulatory guides to endorse ANSI/ANS-2.10-1988, "Guidelines for Retrieval, Review, Processing, and Evaluation of Records Obtained from Seismic Instrumentation," and ANSI/ANS-2.23-19XX on post-earthquake evaluation.

3.12 Exchange of Seismic Research Information Project (Appendix F)

3.12.1 Scope

There is a great deal of research being sponsored by the Japanese Agency of Natural Resources and Energy (ANRE) and by the electric power utilities in Japan that should be of value to the NRC in ensuring the safe operation of nuclear power plants during and after an earthquake. Unfortunately, we are not sufficiently familiar with much of this research to judge how it will complement the NRC Seismic Research Program. It is important to learn first hand what research information and data ANRE and the Japanese utilities may now have, what research they are now performing, and what research they plan to conduct in the future. With this knowledge, we can judge how important the research may be to the NRC and the U.S. industry and what information we may be willing to exchange for it. Receiving appropriate Japanese research information and data will provide the NRC with large savings in research funds in the future. With personal knowledge of the research being performed or planned, ANRE may be persuaded to modify their programs to meet our needs more closely. Personal knowledge and contacts could also result in valuable complementary or joint research programs for the benefit of both parties.

In August 1984, ANRE and the NRC held a joint seismic information exchange meeting. Various programs related to seismic research and sponsored by both participants and industry counterparts were described. From this meeting, four packages of seismic research results and information have been identified for exchange. Each side has information and data to be exchanged in each package. These packages relate to (a) reactor building component model seismic tests and component fragility tests (2.6.3.1, 2.6.3.2, 2.3.3.1, 2.4.3.1), (b) soil settlement and soil-structure-interaction information and data (2.6.3.1, 2.6.3.2), (c) vibration and damping test results and analysis of piping systems (2.6.3.1, 2.2.3.2), and (d) equipment qualification data (2.2.3.1, 2.2.3.2).

It is the purpose of this research program to activate the exchange of information and data related to each of the four information exchange packages.

3.12.2 Integration and Relationship With Other Research

This program for the exchange of seismic research information involves NRC seismic information related to component fragility (3.8), soil settlement (3.2), and the dynamic response of piping (3.7) plus certain information developed by EPRI for the U.S. nuclear industry. The research information and data to be received from the Japanese will be complementary to the NRC seismic research as described in this volume, as well as to the seismic research to be

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performed by EPRI. It is anticipated that this information exchange program will be expanded to include research information related to containment integrity, plant aging and life extension, piping leak before break, and material studies.

3.12.3 Products

The products to be received through this exchange program will be Japanese government and industry reports, files, and possibly computer tapes. These will contain detailed research program descriptions, research information, experimental data and results, and research analysis useful in satisfying NRC seismic research needs. From this program, complementary or cooperative research programs with the Japanese may be established. (Supports regulatory needs 2.6.2.1, 2.6.2.2, 2.2.2.1, 2.2.2.2, and 2.4.2.)

3.12.4 Regulatory Application

The research information and data that will be received from the Japanese will complement the results obtained from NRC-sponsored seismic research. These results will be developed to satisfy regulatory research needs as identified in the various research programs described in this volume.

3.13 Seismic Design Margins Program (Appendix G)

3.13.1 Scope

The current objectives of the Seismic Design Margins Program are to develop and improve guidance for assessing the inherent capabilities of nuclear power plants to withstand earthquakes above the design level (2.2.3.1) and to provide an effective and efficient means to identify vulnerabilities of nuclear plants to seismic events (2.3.3.1). The first objective addresses issues such as the Charleston earthquake in which there may be future needs to reassess the seismic resistance of a plant to earthquakes larger than its current Safe Shutdown Earthquake. The second objective reflects current planning for implementing the Severe Accident Policy Statement for external events (2.3.3.2).

In 1984, the NRC Seismic Design Margins Program was initiated to provide the technical bases for better addressing seismic margins issues. A group of consultants, the Expert Panel on the Qualification of Seismic Margins, recommended a program plan that was endorsed by the NRC Working Group on Seismic Design Margins. The Expert Panel also served as the chief innovator of a new approach for assessing the adequacy of nuclear power plant seismic margins (NUREG/CR-4334) (Ref. 19). The seismic margins approach developed uses screening concepts to focus on only those systems important to mitigating earthquake-induced core melt and to avoid detailed reviews of structures and components known a priori to have sufficient seismic resistance. The figure of merit used is a high confidence of low probability of failure (HCLPF), a conservative representation of capacity that includes the effect of uncertainty. The Lawrence Livermore National Laboratory staff and its

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subcontractors worked with the Expert Panel to develop guidelines for seismic margin reviews (NUREG/CR-4482) (Ref. 27) based on the panel's recommended approach.

In 1986-1987, the major effort of the Seismic Design Margins Program has been the implementation of the guidelines discussed above in the trial seismic margins review of the Maine Yankee plant. While this review was a "trial" in the sense that it serves to demonstrate the use of the new approach, the results of this review have been used to resolve an actual licensing issue for the Maine Yankee plant. In March 1987, both the final report of this review (NUREG/CR-4826, Vols. 1-3) and the safety evaluation report were issued.

A separate project that will be completed in 1987 is the BWR Systems Study. The results of several recent BWR seismic probabilistic risk assessments (PRAs) will be used to develop systems "screening" guidelines that would be equivalent to those already developed for PWRs in NUREG/CR-4482 (Ref. 27).

Another study to be initiated and completed in 1987 is a comparison of the two HCLPF calculational methods recommended in NUREG/CR-4482 (2.2.3.3). The Maine Yankee review has primarily used the "PRA fragility" HCLPF approach, while EPRI has further developed and employed the "Conservative Deterministic Failure Margins (CDFM)" HCLPF approach in their seismic margin review of the Catawba plant.

The current plan is to compare calculations using EPRI's CDFM method with those using the PRA fragility approach. It is generally felt that the CDFM would be more acceptable for use by traditional design engineering groups (e.g., architect-engineering firms) than the PRA fragility approach, but it should be noted that the direct use of experience and test data, when available, is the most desirable approach of all.

A trial BWR plant review is included in the original program plan. Negotiations are now under way to do this review as a cooperative effort with EPRI. Current planning would have the NRC sponsor a thorough review of EPRI's review procedures and the results of the EPRI Catawba review before endorsing or modifying EPRI's approach for use in the upcoming BWR seismic margin review. Cooperating with EPRI will help reduce NRC costs, aid in obtaining utility cooperation for the review, and establish a single review procedure that is acceptable to both the NRC and industry. The BWR review should be initiated in 1987 and completed in 1988.

3.13.2 Integration and Relationship With Other Research

Research addressing seismic response, failure modes, and failure levels has served to better define seismic design margins. Research in these areas includes the Seismic Category I Structures Program (3.3 and Appendix C), the Piping Design Program (3.7), and the Seismic Component Fragility and Ruggedness Project (3.8 and Appendix D). Ongoing studies by the Seismic Qualification Utilities Group have been particularly useful in gathering data and establishing lower bounds of fragility estimates for equipment.

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The Seismic Design Margins Program has made use of results and insights from NRC- and industry-sponsored PRAs. NRC programs dealing with seismic PRA include the Seismic Safety Margins Research Program (SSMRP), which performed risk assessments of Zion (PWR) and LaSalle (BWR). Industry-sponsored seismic PRAs include Millstone 3 (PWR), Seabrook (PWR), Limerick (BWR), Oconee (PWR), Indian Point 2 and 3 (PWRs), GESSAR (BWR), and Kuosheng (BWR). These PRAs were a source of information for the development of seismic design margins screening guidelines.

While the seismic margins approach is purposely separated from seismic hazard prediction, results from the Seismotectonic Program (3.1 and Appendix A) may create issues involving a resolution by a margins review. Of particular importance is the Seismic Hazard Characterization of the Eastern United States Project and future NRR implementation of this methodology.

3.13.3 Products

a. Maine Yankee trial plant review using initial review guidelines to assess seismic margins and seismic vulnerabilities of a nuclear power plant (1987). (Supports regulatory needs 2.2.2.1 and 2.3.2.)

b. Trial plant review of a BWR (1988). (Supports regulatory need 2.2.2.1.)

c. Final review procedures to be used to assess seismic design margins and vulnerabilities of either PWR or BWR nuclear power plants (1988). (Supports regulatory needs 2.2.2.1 and 2.3.2.)

3.13.4 Regulatory Application

This research will result in information that will be used directly in a safety evaluation report involving the seismic adequacy of Maine Yankee. The seismic review methodology developed under the Seismic Design Margins Program will be used in future licensing actions on an as-needed basis.

The seismic margin review methodology developed under this program is thought to be the most efficient and effective way to find seismic vulnerabilities on a plant-by-plant basis. This approach is an explicit part of the current planning to treat external events in the implementation of the Severe Accident Policy Statement (Ref. 15). The Seismic Design Margins Program will be modified as necessary to meet the needs of the final plan to implement the Severe Accident Policy Statement.

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3.14 Reliability Analysis of Nonlinear Behavior of Concrete Structures Project

3.14.1 Scope

After construction, nuclear power plants have had the accident or environmental design loads on their structures increased beyond the original design levels. As a result, there exists a need to improve on current approximate methods used by the NRC staff and licensees to evaluate structural ultimate capacities and design margins. As a step toward meeting this need, a reliability analysis method for concrete containments and shear wall structures has been developed. The method uses a linear (elastic) analysis to model the structural response. Since the structural response to loads higher than original design loads will most likely be substantially nonlinear (plastic), it is desirable to extend the reliability analysis method to incorporate nonlinear behavior. The method will then more realistically model the structural behavior under extreme loads.

In the first year of this 2-year plan, probabilistic, nonlinear structural analysis methods for concrete containments and shear walls will be developed. A random equivalent linearization method idealized in terms of stick models will be developed. Other types of idealizations will be considered if possible (2.2.3.1, 2.2.3.3, 2.6.3.1, 2.6.3.2). Also initiated will be an extension of the Reliability Analysis of Structures (RAS) computer code to include nonlinear structural response. Thus, the basic analytical tools needed to develop a method for analyzing realistically the seismic or accident load limits on plant structures will be provided.

In the second year, development will be completed of the random, probabilistic, nonlinear structural analysis method. This will provide a means of assessing the ability of nuclear power plants to withstand loads greater than original design loads (2.2.3.1, 2.2.3.2). Also completed will be the RAS code extension into nonlinear (plastic) behavior, enabling the NRC staff to independently verify the adequacy of procedures used to compute structural capacities in seismic risk and margins assessments (2.2.3.1, 2.3.3.1, 2.6.3.1). This will complete development of the desired analysis method.

3.14.2 Integration and Relationship With Other Research

This new RES project is related to previous research sponsored by NRR and RES. The earlier work dealt with the development of a reliability analysis method for Seismic Category I concrete structures for accident or environmental loads up to the original design loads. In one project, a reliability analysis method was developed incorporating finite element analysis and random vibration theory. It also incorporated probabilistic characteristics of loads and load combinations. Another contract by NRR developed the RAS computer code, and a linear evaluation of an idealized containment was performed. Under another NRR project, an analytical method and algorithm was

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developed for generating a seismic power spectrum from a given response spectrum (or the reverse if desired). These were then incorporated into the RAS code, enabling it to assess the reliability of concrete containments or shear walls subjected to design loads. A more recent NRR project has concentrated on providing similar capability for evaluation of concrete frame structures.

The work proposed in this new RES project will extend the evaluation and reliability assessment capability to concrete structures subjected to seismic or accident loads greater than the original design loads.

3.14.3 Products

a. A random equivalent linearization analytical technique for concrete containments and shear walls that will model nonlinear (plastic) structural behavior with an equivalent linear (elastic) analysis. This will enable more accurate modeling of structural response limits with an analysis that is not overly complex. (Supports regulatory needs 2.2.2.1, 2.6.2.1, 2.6.2.2.)

b. A reliability analysis method for nonlinear (plastic) behavior of concrete containments and shear walls. This method will use the above technique, using probabilistically derived load values, to determine structural behavior under these loads in seismic PRAs or margin studies. (Supports regulatory needs 2.2.2.1, 2.6.2.1, 2.6.2.2.)

3.14.4 Regulatory Application

The results from this program will enable the NRC staff to independently evaluate the behavior of Category I concrete structures when subjected to loads greater than original design loads. This will be done in support of seismic PRAs and margin studies by generating capacity curves and verifying results of capacity analyses. In addition, this analytical method is being studied by national structural design code committees for possible incorporation in these codes. If incorporated, the NRC would review these codes for endorsement via its regulatory guide program and would apply these endorsed codes in the standard review plan for NRC licensing reviewers. Early use has already been made of the linear (elastic) RAS code in licensing reviews of Grand Gulf, Clinton, and GESSAR II nuclear power plant buildings to independently verify containment structural capacity and its variability.

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GLOSSARY

Acronyms and Definitions

ACRS	Advisory Committee on Reactor Safeguards
ASME	American Society of Mechanical Engineers
BWR	Boiling water reactor
Charleston Earthquake	An earthquake occurring in 1886 in Charleston, South Carolina.
COE	(U.S. Army) Corps of Engineers
Degraded Pipe Program	A program to develop the basic elastic-plastic fracture mechanics analysis methods to allow the structural integrity evaluation of inservice cracked nuclear piping.
EDQP	Environmental Qualification of Mechanical and the Dynamic Qualification of Electrical and Mechanical Equipment Program - a program to develop criteria and methodologies to improve national standards or other regulatory documents used for qualifying electrical and mechanical equipment.
EPRI	Electric Power Research Institute
Event Tree	Describes sequences of system failures which, if they fail in certain combinations, may lead to the release of radioactive material from the reactor to the environment.
Failure	The inability to perform the intended function.
Failure Level	Magnitude of the input load (e.g., acceleration or displacement) causing failure.
Failure Mode	Phenomenon causing failure, e.g., cracking, binding, or collapse.
Fault	A tectonic structure along which differential slippage of the adjacent earth materials has occurred parallel to the fracture plane.
Fault Tree	Describes the various ways by which a system can fail.

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FEMA	Federal Emergency Management Agency
Fragility	The probability of failure at a given failure level.
FRG	Federal Republic of Germany
HDR	Heissdampfreaktor facility - a superheated steam reactor located in the Federal Republic of Germany that has been decommissioned and modified for research.
Holocene Movement	The current geological time period that began approximately 18,000 years ago.
IGSCC	Intergranular stress-corrosion cracking.
Inelastic Response	Plastic flow of material resulting in permanent deformation when the load is removed.
Initiating Event	An occurrence that activates the safety systems of a nuclear power plant.
KfK	Kernforschungszentrum Karlsruhe
LANL	Los Alamos National Laboratory
Meers Fault	A geological fault located in southwest Oklahoma.
MITI	Ministry of International Trade and Industry, Japan.
NBS	National Bureau of Standards
New Brunswick	A January 1982 earthquake occurring in New Brunswick, Canada.
Nonlinear Response	Condition where the response of a component or structure is not proportional to load due to inelastic material behavior or geometry.
NRC	Nuclear Regulatory Commission
NRR	(Office of) Nuclear Reactor Regulation, NRC
NSF	National Science Foundation
NTOL	Near-term operating license
NUPEC	Nuclear Power Engineering Test Center, Japan

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OBE	Operating Basis Earthquake - an earthquake that could reasonably be expected but not affect the operation of a nuclear plant during its life.
PRA	Probabilistic risk assessment
PVRC	Pressure Vessel Research Committee
PWR	Pressurized water reactor
RES	Office of Nuclear Regulatory Research, NRC
Response Spectrum	A plot of maximum responses (acceleration, velocity, or displacement) of a family of idealized single-degree-of-freedom damped oscillators against natural frequencies (or periods) of the oscillators to a specified vibratory motion input at their supports.
RMIEP	Risk Methodology Integration and Evaluation Program
SDMP	Seismic Design Margins Project
Seismic	Pertaining to an earthquake
Seismicity	Relationship of the frequency and distribution of earthquakes.
SEP	Systematic Evaluation Program - a program where 11 of the older operating plants were evaluated against the "intent" of the current licensing criteria for selected issues.
SHCP	Seismic Hazard Characterization Project - the development and application of a seismic hazard characterization methodology for the entire region of the United States east of the Rocky Mountains.
Soil Liquefaction	Any total or near total loss of shear strength of the soil due to cyclic loading.
SQUG	Seismic Qualification Utilities Group
SSE	Safe Shutdown Earthquake - the earthquake producing the maximum vibratory ground motion for which certain structures, systems, and components are designed to remain functional.

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SSI	Soil-structure interaction
SSMRP	Seismic Safety Margins Research Program
SSRAP	Senior Seismic Review and Advisory Panel - panel comprised of NRC and SQUG members to review, advise, and assist on matters related to USI A-46.
Stress Field	Term used to describe forces acting on a geologic structure.
USGS	United States Geological Survey
USI	Unresolved Safety Issue
10 CFR	Title 10 to the Code of Federal Regulations. Title 10 - Energy is composed of four volumes. The first volume, Parts 0-199, contains the regulations of the Nuclear Regulatory Commission.

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A

Appendix A
Seismotectonic Program

NRC Project Manager: Andrew J. Murphy

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APPENDIX A

SEISMOTECTONIC PROGRAM PLAN

EXECUTIVE SUMMARY

Purpose

Seismic hazards are significant contributors to the overall hazard at some nuclear power plants. Estimation of these hazards is a very significant factor in siting of nuclear power plants and evaluating the safety of existing power plants. There is considerable uncertainty in estimating the seismic hazard particularly in the Eastern United States. The objectives of the Structural and Seismic Engineering Branch seismotectonic research are to quantify and reduce the uncertainty in seismic hazard assessment and to develop methods of dealing with uncertainties. The purpose of the Seismotectonic Program Plan (STPP) is to describe (1) the technical and regulatory issues generated by the uncertainty in seismic hazard assessment, (2) the background, including research already performed, leading up to the current program and future program, (3) the research program designed to address the issues, and (4) the application of the results of the program.

The fundamental regulatory issue addressed by the STPP is the seismic hazard assessments used in estimating seismic risk to nuclear power plants. This issue is specifically addressed by confirmatory research in support of the data and analysis techniques used for licensing decisions and by research in support of regulatory guidance and possible revision of the current regulation, Appendix A to 10 CFR Part 100.

The November 1982 U.S. Geological Survey (USGS) clarification of its position on the 1886 Charleston earthquake raised a regulatory issue that needs a timely response. The USGS notes that it has not been able to associate the Charleston earthquake with a geologic structure and that there is a probability, albeit very low, that the level of ground motion associated with a Charleston-sized earthquake could occur elsewhere on the eastern seaboard. Under existing seismic siting criteria, Appendix A to 10 CFR Part 100, the ground motions produced by an earthquake not associated with a specific structure are postulated to occur at any location in the tectonic province within which it occurred. If a nuclear power plant is within that tectonic province, the earthquake is postulated to occur near the plant site. If the plant is in a different province, the ground motions at the site are calculated as if the earthquake occurred on the point on the province boundary closest to the plant.

If the 1886 Charleston earthquake cannot be correlated with a structure, it could be considered to occur anywhere within the tectonic province. Because the tectonic provinces in the East are large, this could result in the postulation of ground motions as large as those of the Charleston earthquake at almost every reactor site on the eastern seaboard. This could have very serious implications for the licensing process.

In 1983, the Geosciences Branch, NRR, developed an interim licensing position and an action plan to address the Charleston issue. The action plan was transmitted to the Division of Health, Siting, and Waste Management (DHSWM) via

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a memorandum dated March 22, 1983, from Vollmer to Arsenault with a response dated May 20, 1983.

Three issues contribute to the uncertainty in seismic hazard assessment; the program plan is organized around them. Those issues are (1) the uncertainty in establishing seismic source zones or structures, (2) the uncertainty in the propagation of seismic energy, and (3) the uncertainty in the site-specific ground-motion response of the site, including soil failure. The program as it has been conducted in the past and will continue to be conducted in the future consists of three parts: regional programs that address the uncertainty in seismic source configurations and seismic energy propagation; topical programs that deal with developing site-specific spectra, strong ground-motion models, and soil failure models; and probabilistic programs that deal with techniques to handle the uncertainties.

The regional program consists of seismological and geological/geophysical programs in the Southeast; the Northeast; the New Madrid/Anna, Ohio area; the Nemaha Uplift area; the Frontal Fault System of New Mexico, Texas, Oklahoma, and Arkansas; and the Pacific Northwest. The results from the seismic networks help define the zones of active seismicity and the basic seismological parameters of that activity. The geologic/geophysical investigations attempt to verify the proposed seismic zonations and seismogenic mechanisms. This is necessary because of the short seismic history in the United States.

Another issue that has arisen as a result of the discovery of substantial prehistoric but geologically recent displacement along the aseismic Meers Fault in south central Oklahoma is the validity of placing strong reliance, as the NRC has done in the past, on the presence or absence of seismicity in determining the seismic potential of faults in the Eastern United States. Several program are being funded to look into this issue.

The topical programs include analysis of strong motion data from the Eastern United States and selected sites in California and analysis of seismic energy propagation. Validation of soil failure models will be examined. The probabilistic programs include a study of the sensitivity of predicted seismic ground motion to variations in models of seismic source zones. A previous study, the Systematic Evaluation Program (SEP), which used expert opinion to evaluate older nuclear power plants, has been improved and expanded for use in the short-term, probabilistic resolution of the Charleston problem.

The results of the Seismotectonic Research Program will continue to be used to expand the geological, seismological, and geophysical data base with which to evaluate future sites, decrease the number of uncertainties that must be dealt with, develop better methods to handle uncertainties, update regulations and guides, and provide the bases for any seismic reanalysis of existing nuclear plants that may be required.

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1. INTRODUCTION

Seismic hazards are significant contributors to the overall hazard at some nuclear power plants. Research directed at estimating and reducing the uncertainty in the seismic hazard and research directed at coping with the uncertainty are central themes of the Seismotectonic Program Plan (STPP). It is a Structural and Seismic Engineering Branch RES position that the uncertainties in seismic hazard assessments are higher in the Eastern United States than in the Western United States (the eastern foothills of the Rocky Mountains constitute the dividing line). Because the majority of nuclear power plants are in the East, the research is concentrated there.

Three of the principal sources of uncertainty in establishing seismic hazards in the East are uncertainties in the seismic source zones, the propagation of seismic energy, and the site response.

The Charleston 1886 earthquake is an example of how these three factors combine in the East to produce high uncertainties. The 1886 earthquake has not been associated with a structure in Charleston; thus, it might be assumed to have an equal probability of occurrence throughout the eastern seaboard. Although the Charleston earthquake was of about the same magnitude as the 1971 San Fernando Valley earthquake, the Charleston earthquake had about 10 times the area of equivalent damage. The site-specific response throughout the Coastal Plain is additionally complicated by the possibility of severe differential soil settlement and soil liquefaction leading to severe differential structural settlement. Thus all these factors contribute to produce an overall high uncertainty in seismic hazard estimate on the eastern seaboard.

Research is being conducted to address each of these sources of uncertainty and also to provide methods to handle or cope with the uncertainties in a regulatory environment. These projects include development of "probabilistic" techniques for estimating seismic hazard curves and recurrence information for long return periods. The increased use of probabilistic risk assessments (PRAs) for analysis of nuclear power plant sites has created a need for this type of study.

Probabilistic assessment of risk requires methodologies to handle the uncertainties in seismic hazard assessments. The present licensing criteria are "deterministic" and are based on procedures in Appendix A to 10 CFR Part 100. The probability of ground shaking above the design level is not explicitly considered. However, PRAs show that a major contributor to risk is earthquakes several times the design level. Three approaches are presently being used to develop a probabilistic approach to handle the known uncertainties: expert panels, formal sensitivity studies, and examination of methods of estimating recurrence rates.

The issues in seismic hazard assessment are addressed in this document in four sections.

Section 1. The technical issues of seismic hazard assessment, which are described in the remainder of this section.

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Section 2. Background that describes past programs and those old programs that are still ongoing.

Section 3. Current and future research programs to address the technical issues, including a discussion of the relationship of other research programs to them.

Section 4. The application of the results of the research program to the user needs.

1.1 Technical Issues

The fundamental technical issues addressed by seismotectonic research are how to quantify and reduce the uncertainties in seismic hazard assessments and how to develop techniques to deal with the uncertainties in a regulatory environment. These issues are closely related. The more accurately the principal contributors to the uncertainty are quantified or understood, the more precisely the contributors can be handled in a regulatory environment. These issues are discussed below in the Sections 1.1.1, Hazard Uncertainties, and 1.1.2, Handling Uncertainties.

1.1.1 Hazard Uncertainties

As noted earlier, three of the principal contributors to the uncertainty in quantifying the seismic hazard at a site are the characteristics of the seismic source, the propagation of seismic energy between the source and the site, and the site response, including soil response. The relative levels of contribution of these three to uncertainty are region dependent. (For programmatic ease, the Eastern United States has been divided into four regions: Northeast, Southeast, New Madrid/Anna, Ohio, and Nemaha Ridge/Meers Fault.) Currently, there is a reasonable level of confidence in a working hypothesis for the source of seismicity in the New Madrid area and a moderate understanding of some of the regional propagation characteristics. There are a number of hypotheses for the source of Southeastern seismicity, including the Charleston, South Carolina area. No generally accepted hypotheses are available for the Northeast or the Nemaha Ridge. There is a low level of knowledge about the propagation and site response characteristics in the East except as noted for the New Madrid region.

Source zone uncertainties are the most visible problems on the eastern seaboard. This was underscored by the 1982 United States Geological Survey (USGS) clarification of position on the 1886 Charleston earthquake. That position established the Charleston seismicity as an Atlantic seaboard earthquake problem. In the opinion of the USGS, there is an insufficient historical data base to establish seismic zonation on the basis of seismicity alone, and the causative mechanisms of eastern earthquakes are, with few exceptions, not known.

In areas like the Eastern United States, this inability to identify the causative mechanisms is particularly difficult to deal with; knowledge of the causative mechanisms can be used to compensate for the lack of a long historical data base by establishing source zones on the basis of geology. Studies of the Chinese data base have shown the validity of that approach, i.e., determining the causative mechanism. Unfortunately, studies of that same data base have shown that, without the causative mechanism, the 2000+ year seismic history is

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too short for seismic zonation if the source zones cannot be constrained on the basis of geology.

The issues are presented in two groups: regional issues, which are mainly issues of seismic source zone uncertainties, and topical issues, which are issues of seismic attenuation, site-specific spectral analysis, and soil liquefaction.

1.1.1.1 Regional Issues

There are four eastern regional programs and a limited regional program in the Pacific Northwest. In the regional areas there is one basic problem: lack of knowledge about the cause of the seismicity. The problem is fundamental to the other problems of seismic source zone uncertainties, which are the locations of potential future seismicity and the magnitudes and frequencies of that seismicity. In some areas experts have more confidence in the seismic zonation than others. A short discussion of the source zone issues for each of the regions follows.

1. Southeastern United States

The 1886 Charleston earthquake dominates the seismic history of the Southeastern United States. The cause of that earthquake is not known. Numerous hypotheses have been proposed, mostly involving reactivation of older faults and implying the possibility of Charleston-like motion elsewhere in the Eastern United States. Faults that cut Mesozoic and Cenozoic sediments have been found by seismic refraction and reflection investigations in the Charleston region; however, the faults do not cut the surface. The Cooke Fault and the Helena Banks Fault, both trending NE, are examples of this. The Bel Air Fault near Augusta cuts Mesozoic beds and also trends NNE. None of these faults has been demonstrated to be seismogenic or even active in the Quaternary. There are other areas of seismicity in South Carolina in addition to the Charleston area, but the relationship of that activity to Charleston activity is yet to be clearly established.

Two other areas of significant seismicity in the Southeast are the Giles County and Central Virginia Seismic Zones. In these areas some progress has been made toward the correlation of seismicity with structure.

Preliminary data from the Central Virginia Seismic Zone show the possibility of correlation of earthquake hypocentral locations and a structure defined by seismic reflection profiling. Good-quality hypocentral locations are available because of the station distribution and a good velocity model of the area. Excellent information on crustal structure was available because of detailed geologic mapping, good magnetic and gravity data, and a state-of-the-art seismic reflection profile. The locations of earthquake hypocenters apparently correlate spatially with ESE dipping listric faults that are splays of the decollement. No fault plane solutions are available with which to determine the senses of motion; therefore, positive association of earthquakes and faults on a one-to-one basis has not been made.

Recent developments on the stress field in the Southeast raised questions about the sense of motion on faults previously considered unambiguous. The Stafford Fault Zone of northern Virginia is a NNE trending fault zone that shows about a hundred meters of reverse motion. Previously it was considered that

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the direction of stress east of the Blue Ridge was NW-SE directed, consistent with the reverse motion of the Stafford Fault Zone. New data suggest a N60°E direction of the maximum compressive stress. If this direction is correct, the Stafford, Bel Aire, Cooke, and Helena Banks Faults all could be primarily strike-slip faults. The observed vertical components could be secondary.

This new stress information is critical for interpreting the Central Virginia Seismic Zone. If the stress direction is correct, the listric splay of the Central Virginia Seismic Zone may be reactivated as a primarily strike-slip fault, and motion along the decollement would be secondary.

The hypocenters in the Giles County Seismic Zone are mostly below the decollement surface. Consequently, the observable structure at the surface or in the first few kilometers are not expected to give information useful in interpreting the seismicity there. Previous hypocentral locations have delineated a source zone of the seismicity, which is proposed to be a deeply buried fault system. The existence of such a structure is consistent with the tectonics of the area.

2. Northeastern United States

The seismic activity of January 1982 dominates the recent seismic history of the Northeast. The magnitude 5.7 and 5.0 earthquakes in New Brunswick and the magnitude 4.7 in New Hampshire supplied critical information. There are now over 15 strong motion records from those events and the aftershock sequences. Although structures are observable on the surface, no cause and effect relationship has been generally accepted. The most significant geologic development in New England since the first version of this seismotectonic plan was written is the apparent clarification of the issue of the stress direction in the New England area. The direction of maximum compressive stress throughout the region is most likely about N50°E to N80°E. This is the same as the direction in the midcontinent. Previously, it was thought to be oriented about NW-SE and to also have the same orientation in the Southeast. This new direction is supported by three different studies: a utility study of the seismicity of the Ramapo fault zone, deep hydrofracture stress measurement in New York State by Dr. Marc Zoback of the USGS, and an NRC-funded USGS investigation along the coast of Maine using shallow stress measurements.

An important implication of this stress direction concerns the Ramapo fault system. There is a coincidence of seismicity with the Ramapo and other fault systems in the Highlands, although the cause and effect relationship is not established. The Ramapo fault system forms the western boundary of a Triassic basin. A N50°E stress field would act on those structures to cause a strike-slip-type motion. Previously, most reactivation mechanisms proposed for pre-existing faults have been gravity backsliding or reverse motion. Detailed geological mapping of the surface expressions of faults of this system has been accomplished, but no evidence of recent displacement has been found.

Seismicity and other recent crustal movements in the Passamaquoddy Bay area may be related to reactivation of the Triassic basin in the Bay of Fundy. Recent stress measurements indicate that the basin would be reactivated in oblique normal faulting. This area is important for the "Triassic Basin" hypotheses of eastern seaboard seismicity. The Bay of Fundy basin is similar in

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both structure and dimension to the true continental rifts, such as the Rhine Rift, the Reelfoot Rift, or the East African Rift system. The Bay of Fundy basin shows a very strong magnetic signature, magnetic highs paralleling the edges, that is consistent with mantle involvement in the structure. (This is different from most Triassic basins, which are probably restricted to the crust.)

3. New Madrid Region

The seismogenic mechanism in the New Madrid region is the best understood of any in the East. A zone of seismicity follows the trend of a basement rift, the Reelfoot Rift system. The zone of the very severe 1811-1812 main shock sequence is centered about an offset in the rift that also is the location of a zone of uplift. The proposed seismogenic mechanism is the reactivation of the rift as a strike-slip fault zone. This is consistent with the structure, fault plane solutions, and stress measurements.

The extent of the seismic source zone to the north and south has been an issue in the past. Geophysical data, taken along the proposed northern continuations, indicate a much less profound structure than in the Mississippi Embayment and thus suggest that an earthquake similar to those of the 1811-1812 New Madrid sequence is not likely along these extensions. Some short extensions of the rift are apparent to the northwest, but if the model of rift reactivation is correct, they should not be significant seismic source zones because the stress field will not be properly oriented to reactivate the segments into a strike-slip system. Geophysical evidence also, along with the seismicity, indicates that the southern extension terminates well north of the buried Ouachita Tectonic Front.

4. Nemaha and Meers Fault Region

The Nemaha Uplift in the Central United States is associated with moderate earthquake activity. Together with the Midcontinent Geophysical Anomaly, the uplift may represent a rift zone that is accompanied by clastic-filled basins on the east side, the basins being separated from the rift zone by a series of faults. The Humboldt fracture zone in eastern Nebraska and Kansas represents such a fault that is associated with seismicity. The Thurman Redfield and Northern Boundary fault zones in Iowa have been intermittently active since Paleozoic time.

Elsewhere, the relationship between the uplift and the seismicity is not very clear. However, seismic activity is present all along the Nemaha Uplift. The activity seems to occur particularly at locations where NW trending structures or anomalies cross the Nemaha Uplift.

Another issue is the seismic capability of the Meers Fault in southern Oklahoma and other similar faults that comprise the Frontal Fault System of Texas, Oklahoma, and Arkansas. An important part of this issue is that the Meers Fault is the first demonstrated capable fault in the Eastern United States. Geological evidence indicates the occurrence of several prehistoric, Holocene, large earthquakes, but the fault currently appears to be aseismic. The outcome of research could have an effect on the way the seismic potential of Eastern United States faults is assessed in that a great deal of weight is now given to the presence or absence of seismicity in deciding whether or not a structure has the potential to generate a damaging earthquake.

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5. Pacific Northwest Region

The Pacific Northwest is a region that is characterized by subduction zone tectonics, which, although consistent with most of the eastern Pacific Ocean, makes it distinct from the strike-slip tectonics to the south in California and to the north along the coast of British Columbia The regional seismicity may be associated with the subduction zone beneath Washington and northern Oregon. The outstanding seismic issue is the characterization of the current tectonics of the region; i.e., is the subduction zone seismic or aseismic? Does it have the potential of generating a great thrust earthquake? Is there a seismic gap? What other features are controlling the seismicity? What are the characteristics of strong ground motions from a great earthquake related to this subduction zone?

6. California

Since the el Asnam, Algeria earthquake, coseismic folding has been identified in several recent worldwide events, including the 1983 Coalinga, California earthquake. Active faults that do not break ground surface are often expressed by folding in overlying strata that are not cut by the fault. The relationship between coseismic folding and faulting, and identifying and defining the active faults beneath the folding, is a critical issue, particularly in California.

1.1.1.2 Topical Issues

There are a number of issues that are less amenable to regional characterization and are called topical. These include propagation/attenuation characteristics, soil response studies, and strong ground-motion studies. They are basically ground-motion issues and will be considered in this section in the direction of propagation, i.e., from source to receiver site.

1. Source Parameters

The issue involves the proper characterization of source parameters for Eastern U.S. earthquakes. These parameters include source spectra, dynamic and static stress drop, duration, focal mechanism, corner frequency, moment, and magnitude. Knowledge of these parameters and how they vary with earthquake location and size is critical to understanding eastern earthquakes.

The stress drop, focal mechanism, and source spectra provide significant constraints on the source models and the state of stress within active tectonic/geologic features.

Records from the 1982 New Brunswick, New Hampshire, and Arkansas earthquakes and the 1986 northeastern Ohio earthquake appear to have a strong high-frequency component. This could have significant impact on the type of plant components that would be susceptible to damage from a small nearby earthquake.

2. Propagation/Attenuation Characteristics

There are several aspects of the propagation of seismic energy that are problematic. They are the variation of the attenuation function with distance

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(lateral heterogeneity) and the dependence of "Q,"* the attenuation factor, on seismic wave frequency and direction of motion.

Some very promising work has been done on attenuation by St. Louis University and the Massachusetts Institute of Technology with partial NRC support, but this must be broadened to more fully address the problems mentioned above, particularly the frequency dependence of "Q". Dr. Singh's work at St. Louis University has provided some rudimentary information on the regional variation of "Q" between 0.5 and 3.5 Hz. Information about the high-frequency component of motion is important for the NRC.

3. Site Response Characteristics

Under this issue there are two basic problems, calculation of site-specific response spectra and estimation of the site soil response. Site-specific spectra may be used as substitutes for Regulatory Guide 1.60. Guidance for acceptable techniques that may be used to calculate site-specific response spectra is provided in Lawrence Livermore documents "Seismic Hazard Analysis," NUREG/CR-1582, and "Seismic Hazard Characterization of the Eastern United States: Methodology and Interim Results of Ten Sites," NUREG/CR-3756. A problem that exists in calculating site-specific response spectra is that there is a lack of of data on site conditions, distances, and magnitude ranges.

Also included in site-specific response is the issue of the partition of seismic energy between the horizontal and vertical components. The work of Dr. Gupta of Teledyne Geotech indicates that the ratio of the "average" horizontal to vertical acceleration may vary by as much as 200-300%.

4. Soil Failure

Many nuclear power plants in the East are sited on soil. Soil settlement and liquefaction can become a significant issue when ground shaking greater than the SSE is considered. There are numerous predictive models for soil settlement and liquefaction, but there has been little work to validate them.

1.1.2 Handling Uncertainties

A fundamental issue that needs to be addressed concurrently with attempts to quantify and reduce the uncertainty in seismic hazard assessment is how to handle the uncertainty in a regulatory environment. Some of the techniques used to handle the seismic hazard uncertainty require further analysis and development.

Two significant factors affect the implementation of STPP research results into regulatory decisions: (1) how the results will be used in regulatory decisions and (2) the nature of the results to be used. Probabilistic risk assessment (PRA) is one technique that takes the results from STPP and builds a tool that can be used in the regulatory process. Thus, part of the RES responsibility under STPP would be to make certain that the STPP results and their associated uncertainties were in a form compatible with PRA techniques. A number of PRAs that have included external events have identified seismic hazard as one of the dominant contributors to overall risk.

*"Q" is the attenuation factor and is inversely proportional to the decrease in amplitude of a seismic wave as it passes through a medium, i.e., the higher the "Q", the smaller the change in amplitude.

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Historically, seismic design parameters are presented in terms of anchor-point acceleration values and then regulatory guide spectra. These are not the input specifications that PRA practitioners can most accurately and easily handle. They would prefer input in the form of probability density distributions of ground motion incorporating estimates of sensitivity to spectral distribution, duration, mode, and the like. Development of that type of information requires improvement of existing methods and development of new ones to handle the individual uncertainties and their interrelated sensitivities. This is an important step in the development of techniques to compare the seismic risk at two different sites or to compare the relative significance of internal and external contributors to the overall risk. However, within the timeframe of a normal life cycle of a nuclear power plant, there will always be some uncertainty in the assessment of seismic hazard on the eastern seaboard. This uncertainty needs to be factored into the decisionmaking process.

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2. BACKGROUND

2.1 Status of Research

The program plan that has been carried out over the past several years to resolve the technical issues described in Section 1 is presented here in a parallel format. There are two parts: programs related to quantification and reduction of uncertainty in seismic hazard assessment and programs related to dealing with the uncertainty. The programs described in the first part generally involve basic data collection and interpretation. The programs described in the second part generally involve probabilistic analysis of existing data sets. Research that is ongoing in the current program and that planned for the future, which are described in Section 3, can also be placed in either of these two categories.

2.1.1 Estimation and Reduction of Uncertainty

The programs concerning the estimation and reduction of uncertainty are grouped into regional programs and topical programs. The regional programs consist of operation of seismographic networks and geophysical and geologic investigations of key regions. The topical programs consist of studies related to generic issues rather than source zone problems. There is some overlap; for example, the seismographic networks also contribute to the topical program.

2.1.1.1 Regional Programs

The uncertainty in the characterization of seismic source zones is the fundamental issue addressed by the regional programs. This uncertainty arises from several aspects of the issue: delineation of the seismic source zone, estimation of the maximum credible earthquake, characterization of source parameters, occurrence relationships, and the like.

The programs have been subdivided into the previously described four regions. This subdivision is partially because the nature of the problems or issues vary with the regions and the tectonic processes may differ in the different areas.

The role of the seismic networks as the mainstay or backbone of the regional part of the STPP will be described in the following subsection. This subject is separated from the regional presentation of the program plan so that the common element for the networks will not have to be repeated for each region.

Regional Seismographic Networks

The four regional networks have been the mainstay of the regional STPP. The NRC has also provided funding in a cooperative agreement with the USGS for downhole seismic instrumentation and seismic wave propagation in soil experiments at Mammouth Lakes, California. This research will be expanded through future ground-motion experiments at Anza, California, involving the NRC, USGS, and the U.S. Army Corps of Engineers and the Commissariat a l Energie Atomique (CEA) of France. These two topics are described in the next section. Operation

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of these networks has provided data of primary importance in identifying seismic source zones, depth, recurrence statistics, attenuation information, earthquake source parameters, and other basic seismological data. The four regional networks are:

1. The Northeastern United States Seismographic Network (composed of six local networks, about 130 stations);

2. The Southeastern United States Seismographic Network (four local networks, about 65 stations);

3. The New Madrid/Anna, Ohio, Seismographic Network (three local networks, about 65 stations); and

4. The Nemaha Ridge Seismographic Network (two local networks, about 25 stations).

As part of the previous STPP, a program was initiated to promote the upgrading of seismographic network instrumentation. The first phase consisted of the transition from analog recording to full digital recording of digital signals, i.e., conversion to digital recording of analog signals. The second phase consisted of development of a number of high-quality digital test stations to provide digital signals for several networks.

The issues that this upgrading and testing addressed were twofold. The first was mainly economic, and the second was the number of significant seismological problems that are critical to siting nuclear facilities and do not appear to be readily solvable with the current narrow-band limited-dynamic-range seismographs. One of these significant problems is hypocentral depth determinations.

Significant progress has been made in specifying the epicentral location of recent seismicity in the East. However, the depth is still difficult to obtain. It recently became apparent that, without either more seismographic stations or new analytical techniques, the depth was going to remain elusive. The proposed solution of increasing the information content of the current recording capability at a number of test stations was determined to be more economical and scientifically productive than adding more stations. By increasing the information content, it has become possible to reduce the uncertainty in the depth term by making greater use of the earthquake time series. Accurate knowledge of the depth of epicenters is required for correlation of seismicity with "suspect" geologic structures. There is apparently little correlation between seismicity and surface-mapped geologic features. Uncertainty about the depth of seismicity and the subsurface trend of the feature contributes significantly to this lack of correlation. Accurate depth information is also required as input to fault plane solutions earthquake modeling codes used to generate synthetic seismograms, spectra, and attenuation information.

An extremely important part of the seismic monitoring program has been the capability of the NRC contractors to set up temporary networks composed of portable seismographs within hours after the occurrence of significant earthquakes within their respective regions.

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Relationship Between Seismographic Networks and Geological and Geophysical Investigations

However different the regional issues are, the relationship between the seismographic networks and the geological and geophysical studies remains the same. The networks provide the basic seismicity data, location, depth and magnitude, which are the fundamental data for establishing the seismic source zones and the recurrence relations in them. This information is used to select the areas that are currently seismically active and where geological and geophysical investigations are most likely to be productive. One of the primary objectives of the STPP has always been, if possible, to determine the relationship between seismicity and tectonic features.

One of the important contributions of the geological and geophysical investigations is their ability to augment a short seismic history. Geological and geophysical investigations such as stratigraphic studies and geodetic studies can confirm delineation of seismic source zones by "lengthening" the seismic record, in situ stress measurements can confirm focal mechanism-derived stress directions, and seismic profiling can confirm crustal structure models. With the added dimension of geological and geophysical investigations, the characteristics of seismic source zones can be established with more confidence.

1. Southeastern United States

A primary issue in the Southeast has always been, and still is, the determination of a causative mechanism or structure of the 1886 Charleston earthquake. A number of hypotheses have been proposed, and the major effort of the STPP in the Southeast has been testing these hypotheses for their relevance to eastern seismicity both in the immediate Charleston area and in other areas in the Southeast. The USGS is the prime contractor to the NRC in the immediate Charleston area; its program there is partially funded by the NRC and the USGS.

The program in the Southeast over the past few years has been comprised of the following geological and geophysical projects.

a. Seismic Reflection Profiling in Giles County, Virginia

The purpose of the project was to investigate a postulated structure suggested to be the source structure of the Giles County seismic zone. A deeply buried planar structure, interpreted as an Iapetan normal fault reactivated by modern stresses, has been proposed as the source structure based on the alignment of seismicity. This project made use of some state-of-the-art Vibroseis techniques developed by a Virginia Polytechnic Institute (VPI) consortium to penetrate the shallow karst structures in Giles County. This was a cooperative cost-sharing project coordinated by VPI with State, Federal, and oil industry support. The NRC support was about 10% of the total cost.

b. Seismic Reflection Profiling and Supportive Geology in Central Virginia

The primary purpose of the project was to determine the structure of the earth at hypocentral depths in the Central Virginia Seismic Zone. Preliminary studies showed a promising correlation of earthquake hypocenters with structure

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defined by multichannel seismic studies. The structures are visible at the surface as lithologic boundaries that are fault controlled, but earthquakes and tectonic structures have yet to be correlated on a one-to-one basis. The supportive geology included neotectonic studies of young deposits to determine if there has been recent movement. A traverse parallel to the James River has been completed. A traverse along the Roanoke River, outside the Central Virginia Seismic Zone, is under way.

c. Neotectonics of Southeast

The purpose of the investigation was to gain neotectonic information along several proposed seismogenic structures in the Southeast to see if there was evidence that they had been reactivated. Several kinds of tectonic structures were investigated, including Triassic basins and structures related to the decollement, but no evidence was found reflecting recent displacement. Ongoing and future neotectonic studies are concentrating on paleoseismic evidence in soils. This research is described in the next section.

d. In-Situ Stress Measurement

The direction of in-situ stress defines what faults can be active in a region and how they can move. Several measurements have been conducted at critical locations. Measurements were conducted in the Central Virginia Seismic Zone, where the structure and the distribution of earthquakes were relatively well known. The stress information has provided important information on the type and direction of motion occurring on the faults in the Central Virginia region.

e. Charleston Clarification Project

A project was initiated in FY 1984 to solicit information critical for testing hypotheses on the cause of the Charleston event. The project was built on results of the USGS program, the neotectonics, and the in-situ stress projects. The primary emphasis of the Charleston project at the present time, in addition to the continuous seismic monitoring, is the identification and analyses of 1886 earthquake-induced soil deformation features and similar features that were caused by prehistoric moderate-to-large earthquakes. These projects are described in the next section.

f. USGS Charleston Projects

The USGS has been a major investigator in the Charleston region. This work was cooperatively funded by NRC and USGS. The work includes operation of a seismographic network that has been upgraded during the past 4 years to include some three-axis instruments. Considerable seismic reflection profiling has been conducted both onshore and offshore. This led to the discovery of the Helena Banks and Cooke Faults. Several deep boreholes and many shallow boreholes were drilled to define the stratigraphy of the region. Present studies by the USGS (partly funded by the NRC) and an NRC contractor, which are described in the next section, are under way to locate and assess seismically induced liquefaction and paleoliquefaction features.

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Future work in the region may continue similar types of projects. The impact of the USGS clarification of its position on Charleston is being fully factored into the annual formulation of the USGS-NRC program.

2. Northeastern United States

In the Northeast there are some structures postulated by some scientists as being potentially seismogenic, such as the Ramapo fault system, and certain phenomena that may be related to seismogenic mechanisms, such as the rapid crustal subsidence along the coast of Maine. However, the level of understanding is not as well developed as in the Southeast where several models have been proposed and can be tested. In the Northeast the models are being developed.

The Ramapo Fault is a significant structure that has been studied in considerable detail for many years. There is an apparent cluster of earthquake epicenters in the region of the Ramapo and other faults in the New Jersey-Hudson highlands and the Newark basin. The geology of the zone is well known where the Newark Triassic Basin parallels the older Precambrian and Paleozoic features. In-situ stress measurements and multichannel seismic reflection surveys have been conducted under this seismotectonic plan. The results of these studies have increased the level of knowledge about the Ramapo Seismic Zone substantially, but there are still many unknowns about the relationship between structure and seismicity. However, the compressional stress direction and focal mechanism calculated from the earthquake do not indicate that the Ramapo is the fault on which the earthquakes are occurring.

a. State of Maine Cooperative Study

Based on studies performed under a cooperative agreement with the State of Maine to investigate rapid subsidence along parts of the coast, rate of subsidence has been estimated to be up to 9 mm per year. However, recent information indicates that the high rates of subsidence may be partly the result of problems with the data and their interpretation. Seismicity is spatially associated with the subsidence, both of which are occurring along the Bay of Fundy rift. This could be significant in that the reactivation of rifts has been proposed as possible causes of the Charleston and other earthquakes in the Eastern United States.

The State of Maine has also assisted in earthquake investigations in the region, such as the 1982 New Brunswick events.

b. Neotectonics of Northeast/New England

Critical structures have been investigated for evidence of recent movements or reactivation, including a Triassic Basin, the area of the Gaza, New Hampshire, earthquake, areas near the epicenters of recent earthquakes on Long Island, and the Adirondack Uplift. No evidence of recent movements has been found. Paleoliquefaction studies were begun 2 years ago in New England and Pennsylvania and are still under way.

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c. In-Situ Measurements

In-situ stress measurements have been conducted by the hydrofracture technique in the Ramapo Seismic Zone and the Moodus Seismic Zone in Connecticut. Information was obtained that supported an ENE principal horizontal stress orientation previously determined by earthquake focal mechanisms in the Ramapo Seismic Zone and indicated the presence of a local, shallow, northwest oriented maximum stress in the Moodus area that is consistent with the findings from other geological and seismological studies.

Shallow in-situ stress measurements were made in the epicentral area of the 1982 New Brunswick earthquake using the overcoring method. These tests demonstrated the presence of very high in-situ stresses in shallow bedrock, but were inconclusive as to determining the orientations of stress. Research Information Letters 147 and 148 have been distributed describing the results from this research.

d. Seismic Profiling of Ramapo Fault Zone

Six seismic reflection traverses have been made across the Ramapo Fault Zone and adjacent Precambrian highland and Triassic terranes, and one profile was made parallel to the zone to define the structure at hypocentral depths. The cross section locations were chosen on the basis of the well-mapped surface geology and the distribution of earthquakes. Although the nature of the major faults in the zone have been relatively well defined at hypocentral depths, earthquakes and faults have not been correlated on a one-to-one basis.

3. New Madrid/Anna and Northeastern Ohio

The source of seismicity in the New Madrid region is reasonably well established. The seismicity is probably occurring along a continental rift zone. The rift is too deeply buried to be mapped geologically; however, evidence of recent movement is observable at the surface. The most striking surface evidence of recent movement is the Lake County Uplift, which has altered the courses of recent drainage channels in the area. There are also numerous seismically induced sand blows in the region. A regulatory issue in past licensing proceedings was the extent of the rift zone to the north and south. Geophysical data indicate that the rift spreads out to the north into several different branches. Based on the studies under this program, these branches are not considered to have the potential of generating earthquakes as large as the 1811-1812 New Madrid earthquakes, however. The southern extension is considered to terminate well north of the buried Ouachita structural zone.

The relationship of the Arkansas 1982-1983 swarm to the New Madrid activity is not yet known, but the available data derived from a study of many of the earthquakes themselves indicate that the swarm is not directly related to the New Madrid seismic zone.

Immediately following the January 31, 1986 Northeastern Ohio earthquake, NRC seismology contractors from the Northeast, South, and Midwest deployed seismograph networks in that region. The data they obtained contributed to the seismic reevaluation of the region and specifically to the seismic reassessment of the Perry Nuclear Power Plant, which experienced relatively high ground motions at high frequencies.

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4. Nemaha and Meers Fault Region

The research activity in the Nemaha region consists of the operation of a seismic network. Because of the discovery of surface displacement on the aseismic Meers Fault in southern Oklahoma, the NRC has also been funding research in that area conducted by the Oklahoma Geological Survey, the University of Nevada at Reno, and the USGS. Results of these investigations indicate the possible occurrence of several prehistoric, Holocene, moderate-to-large earthquakes on the Meers Fault. Although the fault is aseismic, this is the first documented capable fault in the Eastern United States. Future NRC-funded studies with respect to the Meers Fault and other faults within the Frontal Fault System in Texas, Oklahoma, and Arkansas are described in the next section.

5. Pacific Northwest Region

The research activity in the Pacific Northwest up until the past several years consisted only of the operation of a local seismic network in Oregon. Because of budget constraints, the NRC no longer funds this network. Geological and seismological studies have also been funded since 1983. The Juan de Fuca Subduction Zone, which underlies western Washington and Oregon, is an enigma in that geophysical and geological evidence show that it is actively subducting, but there have been no large historic thrust earthquakes like those that characterize most other active subduction zones. An NRC-funded study of other subduction zones around the Pacific Ocean and comparison with the Juan de Fuca Zone have recently been completed by USGS scientists. The results indicate that the zone has the potential for generating a large to great thrust-type earthquake. A new project, described in the next section, will attempt to locate and evaluate paleoseismic evidence for large prehistoric earthquakes.

6. California Region

Most NRC-funded research projects in California are described in the next section. However, a project conducted by the USGS to investigate the 1983 Coalinga earthquake was partly funded by the NRC. During this study the source structures and mechanisms for this event and its aftershocks were defined, although the principal fault did not break ground surface, and the occurrence of coseismic folding was demonstrated.

2.1.1.2 Topical Programs

The topical program is designed to address the topical issues raised in the previous section.

1. Source Parameters

A number of projects have been initiated under this topical element. The most important of these was the acquisition of a "viable" data base of strong-ground-motion accelerograms of Eastern U.S. earthquakes. This has been accomplished by a continuing project to acquire and install an array of accelerographs in the Eastern U.S. to augment the instrumentation programs of the U.S. Army Corps of Engineers and the Veterans Administration. (The instrumentation for these two agencies is usually at dam sites or veterans

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hospitals.) This project has supported the acquisition and installation of about 50 strong-motion accelerographs. A number of these instruments are deployed close to a "host" institution so that they may be quickly redeployed in the event of a moderate-to-large eastern earthquake.

The NRC has supported and is continuing to support several projects for the analysis and dissemination of some of the existing eastern strong-motion accelerograms, including those from the 1982 earthquakes in New Brunswick, New Hampshire, and Arkansas. As part of the NRC-USGS interagency agreement, the NRC has been funding detailed analysis for the New Brunswick and Arkansas data set and some field work in New Brunswick with the Canadians. This work was intended to develop more precise data on the crustal structure at the New Brunswick site to more fully explain the New Brunswick accelerograms. The reason for the high accelerations for small earthquakes remains a puzzle. The U.S. Army Corps of Engineer records from the New Hampshire earthquakes are available as NUREG/CR-3327 with magnetic computer tapes from the NOAA data center in Boulder, Colorado.

As stated in an earlier subsection, following the January 31, 1986 Northeastern Ohio earthquake, NRC contractors from the University of Michigan, Lamont-Dogherty Geological Observatory, Weston Observatory, Memphis State University, and St. Louis University deployed portable seismographs and obtained data useful in the reanalysis of structures and equipment of the Perry Nuclear Power Plant, which experienced relatively high ground motion at high frequencies.

An explicit program for work under this subelement has not been developed, but work of the above type will continue to be supported.

2. Propagation/Attenuation Characteristics

Much of this work has been carried out as part of the seismic data analysis conducted by the regional networks. It is being highlighted as part of the topical program because of its importance. It is also included here because the data base that is currently available is too sparse to provide propagation information on a regional scale and thus should be handled on a broader scale. (This problem of paucity of data is further addressed elsewhere in this program plan by improvements in network instrumentation.)

The limited amount of available data is being used to the fullest extent possible. Projects being planned will use data from special systems that are currently being operated or were operated in the past by the Departments of Energy and Defense and others for specific limited projects. The data from these sources may significantly augment the network data.

3. Site Response Characteristics

A major effort has been under way in the area of site-specific response development. The exact focus of this effort has been developed based on the result of a major workshop on the subject that was held in July 1983. This workshop was jointly supported by the NRC, USGS, and other sponsors and was designed to establish the state of the art on site-specific response problems. Research since this workshop has explicitly addressed the problem and the representation of ground response in excess of the SSE.

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A project in this area that overlaps with the two previous elements is a project with Structural and Earthquake Engineering Consultants entitled "Selection of Earthquake Resistant Design Criteria for Nuclear Power Plants; Methodology and Technical Basis." This project has been examining the use of geologic data in the characterization of seismicity, the scaling of strong ground motion, and the scaling of response characteristics for various site and earthquake parameters.

4. Soil Failure

Development of a validated model for soil failure has been the goal of the soil failure project. A large number of nuclear power plants are on soil foundations, and, because PRAs have been examining the risk of nuclear failure due to ground shaking at two to three times the SSE, the potential for soil failure has become a contributor to the overall risk. There is presently no validated code for soil failure/settlement.

In addressing this issue, we have taken advantage of the experience of the Corps of Engineers who have long been concerned with the effects of soil failure on their structures. They have considerable experience in both laboratory and field studies. They conducted for the NRC a detailed study of available soil failure codes and concluded that DESRA, a code developed by Professor Liam Finn of the University of British Columbia, was the best candidate code for validation. There were three reasons: the physical basis of the code was the best, the code used standard engineering data, and it had been partially validated by data taken at an artificial island in Japan during an earthquake.

The validation experiments were begun and are still conducted at Cambridge University under a subcontract using soil samples tested in a centrifuge. A sand saturated with glycerine is loaded during each test with model structures and subjected to model seismic loads. Pore pressure and displacements are being monitored during the loading.

In FY 1984, the NRC participated in a soil settlement workshop sponsored through the National Academy of Science, the National Science Foundation, and the USGS.

2.2 Program To Address Uncertainties

The objective of this portion of the STPP has been to develop techniques for the analysis or evaluation of existing data sets. Currently these projects all have some probabilistic aspect.

2.2.1 Seismic Hazard Characterization of Eastern United States

Over the past several years, a joint project between the Offices of Nuclear Reactor Regulation (NRR) and Nuclear Regulatory Research (RES) has been conducted at Lawrence Livermore National Laboratory. It was an outgrowth of the probabilistic seismic input for the Systematic Evaluation Project (SEP) and the Site Specific Spectra Project. It was designed to provide a simplified seismic input for PRA and to be used by NRR for resolution of the issues raised by the USGS clarified position on the Charleston earthquake.

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A principal objective of the Seismic Hazard Characterization Project was to improve the basic project computer code developed for SEP and to produce seismic hazard curves with appropriate sensitivity studies for ten test sites. The project used a solicitation of expert opinion as the source of basic seismological data. The seismicity panel provided seismic source zone maps, estimates of maximum magnitude earthquakes for each source zone, and estimates of earthquake recurrence parameters. The attenuation panel provided input on the attenuation and source parameters that was used to propagate the earthquake ground motion from the source to the site.

The methodologies were developed by Lawrence Livermore under the auspices of NRC, and the project was turned over to NRR for specific site evaluation.

Results for the ten test sites were published in NUREG/CR-3756 in April 1984. These and subsequent results have been used during the past several years by NRR as a licensing tool. It is anticipated that preliminary hazard curves will be available for all Eastern United States nuclear power plant sites in the near future.

2.2.2 Selection of Earthquake-Resistant Design Criteria for Nuclear Power Plants; Methodology and Technical Bases

The proposed topics were grouped into five separate tasks in the 1985 seismic safety research program plans. The first two, carried out during the first year of effort, provided for formulation and selection of models to describe slip rates at known active faults and to scale strong motion close to these faults. The third and fourth tasks, planned for the second year of the effort, updated the direct-scaling relationships of spectral amplitudes of strong ground motion and updated and further generalized the Uniform Risk Spectrum method we developed some 7 years ago (NUREG-0406, Vol. 2). The fifth and final task, planned for the third year of the effort at the option of NRC, produced the recommendation on standard (typical) and special case methods and procedures for use in licensing and combined deterministic with probabilistic methods of analysis for selecting a balanced seismic design basis.

2.2.3 Site-Specific Response Program

This project has begun to develop techniques for calculating site-specific response spectra and specifically addresses the problem and the representation of ground response in excess of the SSE. It was also briefly mentioned in Section 2.1.1.2, "Topical Programs."

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3. PROGRAM PLAN - PROGRAMS UNDER WAY AND FUTURE PROGRAMS

The program plan that has been active over the past few years to resolve the technical issues was presented in Section 2. Many of these projects have been completed, and a number of them are still under way. New programs have been developed based on the knowledge gained over the past decade or so. Ongoing and future programs are described in this section. As in Section 2, the programs are divided into two parts: programs related to quantification and reduction of uncertainty in seismic hazard assessment and programs related to dealing with the uncertainties. The programs described in the first part generally involve basic data collection and interpretation, while those described in the second part generally involve probabilistic analysis of existing data sets.

3.1 Estimation and Reduction of Uncertainty

The programs concerning the estimation and reduction of uncertainty are grouped into regional programs and topical programs as they were in the previous section. The regional programs consist of operation of seismic networks and geophysical and geologic investigations of key regions. The topical programs consist of studies related to generic issues rather than source zone problems. There is some overlap; for example, the seismic networks also contribute to the topical program.

3.1.1 Regional Programs

The uncertainty in the characterization of seismic source zones is the fundamental issue addressed by the regional programs. This uncertainty arises from several aspects of the issue: delineation of the seismic source zone, estimation of the maximum credible earthquake, characterization of source parameters, occurrence relationships, and the like.

The seismic networks continue to be the backbone of the regional program part of the STPP. However, over the next 5 years the operation of regional seismic networks in the Eastern United States will be turned over to the USGS.

Regional Seismograph Networks

The regional seismograph networks are essentially the same now. NRC funding of the four regional networks will continue until FY 1992 as currently proposed, i.e., funding in FY 1992 and no operational support in FY 1993. An agreement regarding the establishment of the eastern portion of a National Seismographic Network to replace the seismic coverage provided by the regional networks has been signed by the NRC and the USGS. This agreement provides that the USGS will assume responsibility for monitoring earthquakes in the U.S. east of the Rocky Mountains. The NRC will provide the USGS $500 thousand in FY 1987, and the sum of $900 thousand in each of the FYs 1988, 1989, 1990, 1991, and 1992. These funds will be used exclusively to acquire the permanent equipment, including operating software, necessary to establish the new network. The USGS will assume full responsibility for the operation of the new stations as they are installed. As indicated above, the NRC will continue to maintain responsibility for its existing seismic monitoring networks through its existing contracts as long as they are needed through FY 1992.

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State of Stress in Central and Eastern United States

The NRC is funding a research program by the USGS to determine the orientations of horizontal principal stresses throughout the Eastern United States by analyzing stress-induced borehole elongations ("breakouts") recorded in commercially available four-arm caliper logs. This information on the stress field orientation is needed for assessing the likelihood of slip on pre-existing zones of weakness as well as understanding the nature and pattern of active deformation in the Eastern United States as inferred from available earthquake focal mechanisms.

1. Southeastern United States

A primary issue in the Southeast is determination of a causative mechanism or structure of the 1886 Charleston earthquake. Past emphasis of research in the Charleston region was to test the numerous hypotheses regarding the cause of the 1886 Charleston earthquake and the relevance of these hypotheses to eastern seismicity in general. Although this goal is still important, the primary emphasis is defining tectonic structures at hypocentral depths and studying near-surface paleoseismic evidence both in the immediate Charleston area and in other areas in the Southeast.

a. USGS Charleston Projects

The USGS is the major investigator in the Charleston region and its program there is partially funded by the NRC. In addition to operating the seismographic network and analyzing the seismic recordings, the USGS has been locating and defining seismically induced liquefaction features caused by the 1886 Charleston earthquake and paleoliquefaction structures created by prehistoric, Holocene earthquakes the same size as the 1886 event or larger. The USGS has mapped many of these features extending along the coast from Georgia to the North Carolina state line. Future work will include more precisely defining the ages of prehistoric events, using radiometric dating techniques to estimate recurrence intervals and performing soil dynamic studies to estimate the levels of ground acceleration experienced.

b. Paleoliquefaction Studies on Atlantic Coastal Plain

Using the knowledge that has been gained over the past 5 years by the USGS and the University of South Carolina concerning seismically induced liquefaction features at Charleston, an NRC contractor is conducting an investigation to locate features similar to those identified in the Charleston area elsewhere on the Coastal Plain from South Carolina to Long Island.

c. Seismic Reflection Profiling and Supportive Geology in Central Virginia

The primary purpose of the project is to determine the structure of the earth at hypocentral depths in the Central Virginia Seismic Zone. Preliminary studies have shown a promising correlation of earthquake hypocenters with structure defined by multichannel seismic studies. A traverse extending parallel to the James River from the Blue Ridge to the Richmond Triassic Basin within the Central Virginia Seismic Zone has been completed along with surface geologic mapping. A similar traverse is now under way farther south parallel to the Roanoke River in a region that has relatively little seismicity. As in

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the James River traverse, analysis of existing core boring logs and surface geologic mapping are being carried out simultaneously with the seismic reflection work. The purpose of this research is to compare the tectonic structures in this aseismic area with the structures that are spatially associated with seismicity in the Central Virginia Seismic Zone.

d. Piedmont Geophysical Project

The NRC is sponsoring a research project by a contractor to reevaluate some existing geophysical data and acquire supplementary additional geophysical information to define potential seismogenic structures within the southern Piedmont. This program was started approximately 2 years ago as part of the research to test the hypotheses regarding the causes of seismicity along the Atlantic seaboard, particularly in the vicinity of Charleston, South Carolina.

2. Northeastern United States

An extensive research program has been accomplished throughout the Northeastern United States to define earthquake source structures or seismic source zones. A big part of this program is still active in the form of the seismic networks described in the previous section. The geological and geophysical work has been completed. This work has added greatly to our knowledge of the tectonics of the Northeast, but precise causes of the seismicity are still unknown. Ongoing and future programs are concerned primarily with neotectonic investigations. These studies include mapping of young strata in areas where earthquakes have occurred to help identify source structures, and detailed study of soil deformation that could have been caused by prehistoric earthquakes, similar to the paleoliquefaction research described in the Southeastern United States.

3. New Madrid/Anna, Ohio Region

The NRC program for the present and the future is the operation of the seismographic networks and the analysis of the data obtained from them.

4. Nemaha and Meers Fault Region

The Nemaha region seismic networks are operated by the Oklahoma, Kansas, and Nebraska Geological Surveys.

The Meers Fault of southern Oklahoma is an enigma in that, largely through NRC- and USGS-funded research, it has been shown to have undergone several episodes of substantial prehistoric, Holocene displacement that suggest the occurrence, during each of those episodes, of a large earthquake. Because in the past the NRC has regarded the presence or absence of seismicity as being an important indicator of whether or not a fault is a potential earthquake generator, the discovery of the Meers Fault causes concern about the validity of this criterion.

Future research with respect to the Meers Fault is to determine its western and eastern extent, define its nature at depth, fine tune the ages of the displacements, calculate recurrence intervals, and explore the Frontal Fault System of Texas, Oklahoma, and Arkansas to determine if there are other young faults within that system. Another fault in the system that is en echelon with the Meers Fault, the Washita Fault in Arkansas, is being investigated for possible geologically young displacement.

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5. Pacific Northwest

The NRC is planning to provide funds for a USGS program to investigate potential paleoseismic soil deformation in western Washington and Oregon. Geological and geophysical evidence have shown that the Juan de Fuca oceanic crustal plate is actively subducting beneath the North American continental crustal plate. Unlike most other subduction zones, there have been no historic large-to-major-thrust earthquakes accompanying subduction. By either identifying evidence for prehistoric, yet geologically young, earthquakes, or conducting detailed investigations and not finding such evidence, it is anticipated that these studies will help determine the nature of the seismic hazard in coastal Northwestern United States.

The NRC is funding a USGS study of the 1985 Chilean earthquake to determine the strong motion attenuation/propogation characteristics within the overriding plate of a subduction zone. These data will be applied in the Northwestern United States to evaluate the seismic hazard in that region.

3.1.2 Topical Programs

The topical program is designed to address the topical issues raised in Section 1 that have not yet been satisfactorily resolved.

1. Source Parameters

The primary focus of this subject is to expand the data base from strong ground-motion accelerograms in the Eastern United States. In addition, the NRC is continuing to fund the analysis and dissemination of strong motion data obtained from recent earthquakes in the Eastern United States.

A specific program for this subelement has not been developed, but gathering and analyzing data will continue to be supported.

2. Propagation/Attenuation Characteristics

Like the preceding topic, much of this work is being carried out as part of the seismic data analysis conducted by the regional networks. It is being highlighted as part of the topical program in both Section 2 and this section because of its importance. It is also included here because the data base that is currently available is too sparse to provide propagation information on a regional scale and should be handled on a broader scale. (This problem of paucity of data is further addressed elsewhere in this program plan by improvements in network instrumentation.) Not only does this include data from NRC-funded networks, but also data from special systems that are currently being operated or were operated in the past by the Departments of Energy and Defense and others for specific limited projects. The data from these sources may significantly augment the network data. The limited amount of available data is being used to the fullest extent possible.

An experiment to measure the propagation or attenuation characteristics of strong ground motions from bedrock through soil (glacial till) has been under way for about 2 years. This research is conducted in the Mammoth Lakes area, which is characterized by frequent moderate-to-large earthquakes. The work consists of collecting data from earthquakes through seismographs installed in

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coreholes at different depths between ground surface and bedrock. The purpose is to acquire strong ground-motion records as the seismic waves travel through the soil.

An outgrowth of the Mammoth Lakes experiment and a similar downhole experiment in the San Francisco Bay area is a multiagency, international cooperative research program to be carried out at Anza, California. The Anza site was selected because it is also in an earthquake-prone area and bedrock is overlain by a soil column that is considered to be more typical of those found near most nuclear power plant sites than either Mammoth Lakes or the San Francisco Bay area. At Anza, seismographs will be installed at specifically defined depths between ground surface and several tens of feet into bedrock.

Several additional ground-motion study projects will use the instruments and data from the Anza array. These experiments will also provide data pertinent to the subject of the next topic.

3. Site Response Characteristics

A major effort is under way in regard to site-specific response. The focus of this effort grew out of a major workshop on site response characteristics held in July 1983. This workshop was jointly supported by the NRC, USGS, and others and was designed to establish the state of the art on site-specific response problems. This work will continue to explicitly address the problem and the representation of ground response in excess of the SSE.

An ongoing project in this area that overlaps the two previous elements is a project with Structural and Earthquake Engineering Consultants entitled "Selection of Earthquake Resistant Design Criteria for Nuclear Power Plants; Methodology and Technical Basis." This project is examining the use of geologic data in the characterization of seismicity, the scaling of strong ground motion, and the scaling of response characteristics for various site and earthquake parameters.

4. Soil Failure

In developing a validated model for soil failure we have taken advantage of the experience of the Corps of Engineers who have long been concerned with the effects of soil failure on their structures and who have considerable experience in both laboratory and field studies. They conducted, for the NRC, a detailed study of available soil failure codes and concluded that DESRA, a code developed by Professor Liam Finn of the University of British Columbia, was the best candidate code for validation. The validation experiments using this code are being conducted at Cambridge University under a subcontract using soil samples tested in a centrifuge.

3.2 Program To Address Uncertainties

The objective of this portion of the STPP is to develop techniques for the analysis or evaluation of existing data sets. Currently these projects all have some probabilistic aspect.

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3.2.1 Selection of Earthquake-Resistant Design Criteria for Nuclear Power Plants; Methodology and Technical Bases

The objectives of this program are to (1) provide for formulation and selection of models to describe slip rates at known active faults and to scale strong motion close to these faults; (2) update the direct-scaling relationships of spectral amplitudes of strong ground motion and update and further generalize the Uniform Risk Spectrum method; and (3) produce the recommendation on standard (typical) and special case methods and procedures for use in licensing and combine deterministic with probabilistic methods of analysis for selecting a balanced seismic design basis.

3.2.2 Site-Specific Response Program

As stated in Section 2.2.3, this project is developing techniques for calculating site-specific response spectra and is specifically addressing the problem and the representation of ground response in excess of the SSE. It was also briefly mentioned under Section 2.1.1.2, "Topical Programs."

3.3 Relationship of STPP to Other Programs

In this section, the STPP addresses its relationships with the three groups with which it is associated. The first group is composed of users of STPP products within the NRC. This group includes NRR, NMSS, DRAA/RES, and DE/RES. The second group is composed of supporters of earthquake hazard research with whom the Structural and Seismic Engineering Branch has informal or formal cooperative agreements. This group includes Federal organizations such as the USGS and FEMA and State agencies such as geological surveys. The third group is composed of private sector organizations.

3.3.1 NRC Seismic Research

3.3.1.1 RES

Research related to the uncertainties in seismic risk is contracted for by three divisions within the Office of Nuclear Regulatory Research: Division of Engineering (DE); Division of Reactor Accident Analysis (DRAA); and Division of Reactor and Plant Systems (DRPS).

DE is concerned primarily with the structural and mechanical response of nuclear power facilities to earthquakes that requires seismic hazard input. In addition to the research described in this appendix, DE supports some research on hazard estimation as part of the Seismic Safety Margins Research Plan (SSMRP). The Seismic Hazard Characterization for the Eastern United States (described in Section 2.2.1) is a spinoff from the hazards part of SSMRP. That project is intended to provide a simplified seismic input for SSMRP use. There is also an interface in soil mechanics. DE sponsors research in soil mechanics concerned with soil settlement, soil failure, and liquefaction and research concerned with soil-structure interaction.

DRAA and DRPS are concerned with seismic hazard as an element in the assessment of seismic risk at nuclear power plants. The Full Scope Risk Assessment Program is a major program that includes external input such as seismic information. This is the principal interaction point among DRAA, DRPS,

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and DE. DE provides information to DRAA and DRPS for development of seismic input.

3.3.1.2 NRR

RES coordinates its research activities on seismic hazards very closely with its counterparts in NRR. As described in Section 2.2.1, NRR and RES have jointly supported the development of the Seismic Hazard Characterization project. RES, in effect, has been sponsoring the development or improvement of a computer code for hazard curve calculations, and NRR has been supporting its use at specific sites.

3.3.1.3 NMSS

NMSS, under the high-level-waste program, sponsors considerable technical assistance in the geologic and geotechnical areas and is concerned with seismic siting and seismic design.

3.3.2 Other Government Agencies

A number of other Federal agencies have research programs associated with seismic hazard evaluation and reduction. A large portion of this other research effort is associated with the National Earthquake Hazards Reduction Program (NEHRP) with FEMA serving as the "Lead Agency." The four major participants in the NEHRP are FEMA, the U.S. Geological Survey, the National Science Foundation, and the National Bureau of Standards. The USGS is the principal agency in this group supporting research related to earthquake hazards in the United States. The National Science Foundation is responsible for fundamental geological and seismological research and for most earthquake engineering research.

In addition to the NEHRP, other agencies such as the Departments of Energy and Defense have programs that provide basic geological, seismological, and engineering data and analysis techniques that are useful to the NEHRP.

3.3.2.1 Federal Emergency Management Agency and the NEHRP

FEMA as the "Lead Agency" for NEHRP is charged with coordinating a national effort to counter the serious earthquake threat in the United States. As stated in the law, its objectives are:

- The development of technologically and economically feasible design and construction methods and procedures to make new and existing structures, in the areas of seismic risk, earthquake resistant, giving priority to the development of such methods and procedures for nuclear power generating plants, dams, hospitals, schools, public utilities, public safety structures, high occupancy buildings, and other structures which are especially needed in time of disaster;

- The implementation in all areas of high or moderate seismic risk, of a system (including personnel, technology, and procedures) for predicting damaging earthquakes and for identifying, evaluating, and accurately characterizing seismic hazards;

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- The development, publication, and promotion, in conjunction with state and local officials and professional organizations, of model codes and other means to coordinate information about seismic risk with land-use policy decisions and building activity;

- The development, in areas of seismic risk, of improved understanding of, and capability with respect to, earthquake-related issues, including methods of controlling the risks from earthquakes, planning to prevent such risks, disseminating warnings of earthquakes, organizing emergency services, and planning for reconstruction and redevelopment after an earthquake;

- The education of the public, including State and local officials, as to earthquake phenomena, the identification of locations and structures which are especially susceptible to earthquake damage, ways to reduce the adverse consequences of an earthquake, and related matters;

- The development of research on

    a. ways to increase the use of existing scientific and engineering knowledge to mitigate earthquake hazards;

    b. the social, economic, legal, and political consequences of earthquake prediction;

    c. ways to assure the availability of earthquake insurance or some functional substitute; and

    d. the development of basic and applied research leading to a better understanding of the control or alteration of seismic phenomena.

In addition to coordinating the NEHRP activities, FEMA leads the effort to improve the seismic safety of Federal buildings and conducts a program of earthquake preparedness planning for areas of high and moderate seismic risk. FEMA was one of the cosponsors of the May 1983 Charleston Earthquake Workshop.

3.3.2.2 U.S. Geological Survey

The U.S. Geological Survey is the principal Federal agency charged with carrying out the geological and seismological aspects of NEHRP. The second objective of the Earthquake Hazard Reduction Act of 1977 (Public Law 95-124 [S.1267]) specifies "the implementation (of NEHRP) in all areas of high or moderate seismic risk."

Without providing an exact definition of the term "high or moderate seismic risk," the USGS is currently carrying out an earthquake hazards and prediction program under the auspices of NEHRP that places an overwhelming majority of its NEHRP funds in California.

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In addition to the relationship between the USGS and the NRC implied by the above, the USGS is the NRC's prime contractor for seismic hazard research in the Charleston, South Carolina area. The USGS also does work for the NRC on the topics of strong ground motion and probabilistic sensitivity.

3.3.2.3 National Science Foundation

The geophysics program of the National Science Foundation sponsors research on earthquake processes and phenomena. The civil and environmental engineering program sponsors work on earthquake engineering and socioeconomic implications of earthquakes. The research supported by DE/RES under STPP interfaces with both the geophysics program and the engineering program at the National Science Foundation.

A principal difference between the DE/RES program and the National Science Foundation geophysics program is that the former is structured to produce a specific product, i.e., earthquake hazard information, and the latter is structured to produce basic scientific advancements.

Coordination between the two programs, NRC and NSF, is very good, as evidenced by the numerous jointly funded projects such as the 1983 Charleston Earthquake Workshop and the Soil Settlement/Liquefaction Workshop. This close coordination and cooperation is fostered by the National Academy of Sciences' Interagency Geophysics Discussion Group.

3.3.2.4 Corps of Engineers

The Corps of Engineers (COE) is concerned with seismic hazard primarily as it affects their structures. They have produced a seismic hazard map of the Central United States and a seismic hazard report for the eastern seaboard. They are actively concerned with the problems of soil settlement and liquefaction.

The Corps maintains an array of strong-motion accelerographs at many of their dams. This is particularly important in the Eastern United States where not many such instruments are deployed. These instruments are deployed to provide COE with data specifically applicable to dam safety so some of the data is not directly applicable to more generic safety problems. In spite of this limitation, DE/RES and COE have been able to successfully cooperate on a strong motion data analysis project. DE/RES and COE are cooperating on a joint project to validate theoretical models for soil settlement or liquefaction induced by earthquake ground motion. COE is contributing to the Anza, California, downhole soil dynamic experiment described in Section 3.1.2 by providing drilling and laboratory testing support.

3.3.2.5 Veterans Administration

The Veterans Administration maintains strong motion seismographs in some of its facilities. Although this is a minor effort, the data from them are potentially very significant.

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3.3.2.6 State Agencies

A number of States conduct research in geology and seismology, primarily through the various State geologic surveys. Generally, their work is more related to economic aspects of geology such as mineral deposits or water resources. Some States do have hazard-related research or research directly related to NRC information needs. The DE/RES presently has cooperative programs with several States to share costs on projects of interest to both.

3.3.3 Private Sector Research

Electric Power Research Institute (EPRI)/NRC Interactions

EPRI has developed a topical report to assess probabilistic seismic hazard in the Eastern United States in response to the USGS clarification of position on the Charleston earthquake and to the NRR plan to address that clarification. The EPRI plan is a parallel, but independent, effort to the hazard assessment conducted by NRR. NRR is using the methodology developed by the joint RES/NRR Seismic Hazard Characterization project mentioned earlier in the STPP. The current EPRI plan is primarily a response to licensing initiative; however, EPRI has also made a research effort to clarify some technical issues. The NRC is now reviewing the EPRI Topical Report. EPRI is kept informed of our activities, and they received copies of previous seismotectonic program plans.

3.3.4 International Research

As described earlier, the NRC is conducting a cooperative research program at Anza, California, to study the propagation of seismic strong ground motion in the shallow subsurface. A partner in this cooperative program, along with the USGS and the Corps of Engineers, is the Commissariat a'l'Energie Atomique (CEA) of France. The CEA is providing the funds to drill several holes into which the downhole seismographs will be placed.

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4. APPLICATION OF RESULTS

Many of the applications of the results of old and discontinued research projects have been discussed in Section 2, or have been described in other documents through the years, and therefore they will not be repeated here. The application of research findings from those programs currently under way or those planned for the future will be presented in this section.

4.1 Estimation and Reduction of Uncertainty

4.1.1 Regional Programs

The historic earthquake record of North America is very short. The source structures generating those earthquakes are essentially unknown, particularly in the Central and Eastern United States. By continuously monitoring earthquakes, we increase that data base considerably; by analyses of the seismograms, the characteristics of the earthquake itself, the source structure, the hypocenter depth, the strong ground-motion attentuation/propagation characteristics of the soils and rocks between the source and recording instruments, and the site effects are learned. All these factors provide the basis for seismic design of new structures or the basis for seismic reanalysis of existing structures and subsequent modifications if required. The recorded data will be used as input to the probability analyses of the seismic risk for nuclear power plants. Seismic information will also be used as bases for new regulations or guides, or for the revision or updating of existing ones such as Appendix A to 10 CFR Part 100, and the Standard Review Plan.

The results of the research with respect to the state of stress in the Central and Eastern United States, along with the information from earthquakes, will provide knowledge about the orientation and magnitude of regional and local stresses. Information of this kind can help to identify those tectonic features that are likely to produce damaging earthquakes.

The current USGS position with respect to the 1886 Charleston earthquake, which acknowledges the possibility that an earthquake similar to it could occur at other locations throughout the Atlantic seaboard, placed a greater urgency on the Charleston area research and other research on the east coast. The research currently is primarily focused on defining the source or sources of seismicity and identifying similar sources in the eastern region. The seismological, geophysical, and geological work will contribute to these goals.

The paleoliquefaction studies at Charleston and elsewhere on the Coastal Plain and in the Northeastern United States are expected to show whether or not moderate-to-large prehistoric earthquakes have occurred in other areas of these regions, provide a basis for estimating levels of ground motions experienced, and provide some knowledge about frequency of occurrence. The information will either support past licensing decisions or provide the foundation for any reassessment that may be necessary regarding the seismic design of nuclear power plants.

The New Madrid region is probably the best-defined seismic region in the Central and Eastern United States, but there are still many significant unknowns. For example, the precise natures of the New Madrid earthquake source structures are not known, and the earthquake potentials of the northwestern,

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eastern, and northeastern arms of the New Madrid zone are unknown. The causes of the Anna, Ohio, and Arkansas seismicity are also a mystery. These issues can best be resolved by continuing to record the seismicity through the networks and analyzing the data. Additionally, since New Madrid is a very seismic area, information on the characteristics of the seismic source, the media through which the seismic waves travel, and the receiving site effects can be acquired. These data will be used in nuclear site evaluations not only in the New Madrid region, but in other parts of Central and Eastern United States.

Except for the seismic networks, most research in the Nemaha region in the near future will be concentrated on the Meers Fault and other faults in the Frontal Fault System, which borders the Wichita, Arbuckle, and Ouachita Mountains.

As described in an earlier section, the Meers Fault is an aseismic fault that has undergone substantial prehistoric displacement in Holocene time (within the last 10,000 years). The objective is to define this fault and determine whether or not other similar faults are present in the Frontal Fault System. Countless faults that are currently aseismic are present in the Eastern United States.

One of the criteria for concluding whether a specific fault is capable or not, lacking other evidence, is the presence or absence of seismicity in the vicinity of that fault. These investigations will help to determine the extent to which that premise is still valid. The findings could have an impact on eastern nuclear plants and also on guides and regulations.

The NRC past position concerning the seismic hazard in the Pacific Northwest, west of the Cascade Mountains, has been that the Juan de Fuca crustal plate is not currently subducting beneath the North American plate, or it is subducting very slowly. This position was based on the lack in the historic seismic record of large-to-great thrust-type earthquakes that characterize active subduction zones around the Pacific Ocean. Since that time, however, geological and geophysical evidence have demonstrated that subduction is occurring at a fairly rapid rate. NRC-funded studies by the USGS, in which the Juan de Fuca subduction zone was compared to other active subduction zones that had experienced large-to-great-thrust earthquakes, resulted in a conclusion by the researchers that a great earthquake was likely to occur on the Juan de Fuca subduction zone. The paleoseismic investigations that NRC and the USGS plan to sponsor will attempt to find evidence for prehistoric great earthquakes or suggest, by lack of evidence, that they didn't occur and the current low level of seismicity is characteristic of this subduction zone. The data that support either finding will be used to reassess the seismic design basis for the WNP-3 nuclear power plant in western Washington and, if necessary, the Trojan Nuclear Plant in northwestern Oregon.

The NRC is funding USGS research regarding the 1985 Chilean earthquake. This study is related to work in western Washington and Oregon in that the ground-motion records, site effects, source characteristics, etc., will be used to characterize a great subduction zone earthquake in the Pacific Northwest if that becomes necessary.

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4.1.2 Topical Programs

The ongoing acquisition, analysis, and dissemination of strong motion data obtained from recent earthquakes in the Eastern United States will expand the data base in this region and will eventually lead to the identification and characterization of seismic source structures or zones. Such an accomplishment will be invaluable in assessing or reassessing the earthquake design basis of nuclear power plant sites.

Downhole seismic experiments such as the one under way at Mammoth Lakes, California, and the one soon to be started at Anza, California, are focusing on two of the greatest uncertainties regarding the estimation of strong ground motions at a specific site as they travel from the source through intervening rocks and soils. The test at Mammouth Lakes has obtained data on the propagation characteristics of seismic ground motions through glacial till. This information will be valuable in any assessment of the nuclear power plants founded on this type of material. The Anza experiment is a follow-on of the Mammoth Lakes study in that it will apply the techniques learned there and assess the strong ground-motion transmission characteristics of soils overlying bedrock that are more typical of most soil at nuclear power plant sites. The information will be used as input to seismic evaluations of these sites. Other ground-motion studies will be made in conjunction with the propagation/attenuation research.

4.2 Program To Address Uncertainties

The programs under this topic as described in preceding sections are developing methods to conservatively handle the many unknowns that remain in geological and seismological issues, even after the most comprehensive deterministic investigations. As more data become available, the data base and analysis techniques are upgraded. The results of these programs are used in PRAs to identify areas in nuclear facilities that are most likely to experience problems.

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ANNEX

NATIONAL CENTER FOR SEISMOLOGICAL STUDIES

One of the truly significant problems that is facing the entire seismological community is the efficient management, both in time and cost, of the data that are currently being collected. A report entitled "Effective Use of Earthquake Data" written by the Panel on Data Problems in Seismology of the Committee on Seismology of the National Academy of Sciences/National Research Council was published in August 1983. To quote that report, "the most important recommendation of this panel is that a National Center for Seismological Studies be established that will overcome the key data management problems that we have identified and enhance the availability and effective use of high-quality data sets by the entire seismological community."

This problem is being addressed through an interagency agreement between the NRC and the USGS concerning monitoring seismicity in the Eastern United States. The following paragraphs describe that agreement:

The purpose of this Interagency Agreement is to set forth a plan for establishing a network of seismic stations for monitoring seismicity in the Eastern and Central United States agreed to by the United States Geological Survey (USGS) and the United States Nuclear Regulatory Commission (NRC).

The frequency of occurrence, geographical distribution, magnitude of earthquakes are important characteristics in assessing the seismic hazard of a region and establishing the design and construction criteria for a critical facility at a specific site. These characteristics are known collectively as the seismicity of a region and can only be determined through the operation of networks of seismometers that record earthquakes and analysis of these recordings.

Under the Earthquake Hazard Reduction Act of 1977 (Public Law 95-124) the USGS is charged with assessing the earthquake hazard and developing earthquake prediction systems in those areas of the United States subject to moderate-to-high seismic risk. The goal of the USGS program is to mitigate earthquake losses that can occur in many parts of the United States by providing research, evaluations, and earth science data for land-use planning, engineering design, and emergency preparedness decisions. Specific objectives of the USGS program are: (a) to evaluate the earthquake potential of the seismically active areas of the United States; (b) to provide assessments of earthquake potential of the seismically active areas of the United States; (c) to provide assessments of earthquake hazard and risk in developed regions exposed to the earthquake threat; (d) to predict damaging earthquakes; (e) to provide data and information on earthquake occurrences to the public and scientific community; and (f) to provide data and estimates of the level and character of strong earthquake shaking to be used in earthquake-resistant design and construction. To carry out this work the USGS supports in-house research in geology, geophysics, and engineering as well as significant supporting activities. This program is augmented and strengthened through support of complementary scientific investigations at universities, state agencies, and private companies. USGS earthquake hazards activities are coordinated with related efforts in the Federal Emergency Management Agency,

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the National Science Foundation, and the National Bureau of Standards through the National Earthquake Hazards Reduction Program.

The NRC has certain responsibilities for ensuring public health and safety in regard to potential hazards associated with nuclear power plants, radioactive waste disposal facilities and other activities involving radioactivity. Thus, the NRC has a strong interest in the delineation, assessment, and mitigation of earthquake hazards in the United States, particularly as they pertain to nuclear power plant and radioactive waste disposal facility siting, design, and construction and operation. Because most of the Nation's nuclear power plants are located east of the Rocky Mountains, the NRC has provided special support for earthquake hazard delineation in the central and eastern regions of the United States. These NRC efforts contribute to the goals of the National Earthquake Hazards Reduction Program as well as the NRC's more immediate needs. NRC-supported studies contribute to (a) the better definition of seismicity by determining the location, recurrence rates, and special characteristics of earthquakes; (b) the quantification for seismic hazard and the reliability of seismic hazard assessments, and (c) the definition of the relationships between seismicity of a region and its geologic structure and tectonics.

Given that the objectives of the USGS and the NRC regarding regional seismicity are so interrelated, they wish to pool their resources to establish a modern seismographic network in the United States east of the Rocky Mountains.

The objective of this agreement is to establish a network of modern, observatory-type seismic stations for monitoring the seismicity in the United States east of the Rocky Mountains.

This objective implies a significant change in approach to monitoring the seismicity of this part of the United States and the eventual replacement of NRC's existing regional seismographic networks with an integrated network of more technically sophisticated stations covering the entire United States east of the Rocky Mountains. The general strategy for the new network is outlined in a 1980 report titled "U.S. Earthquake Observatories: Recommendations for a New National Network" by the Panel on National, Regional, and Local Seismographic Networks of the National Research Council.

ELEMENTS OF AGREEMENT:

1. Beginning with Fiscal Year 1993, the USGS will assume full responsibility for monitoring earthquakes in the United States east of the Rocky Mountains. This monitoring will be accomplished through a new integrated network of state-of-the-art seismographic stations.

2. A joint USGS/NRC working group has prepared recommendations for a plan for the development, testing and installation of the new seismographic stations. Based on these recommendations, the NRC and the USGS will develop an amendment to this agreement which will set forth the Plan for the development, testing and installation of the new stations. The Plan will include:

   a. The number and location of the stations to be built.

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b. A schedule for acquisition of the network hardware and for the commissioning of stations.

c. A protocol for timely access to times series and parameter data recorded by the new network. The protocol will encompass interagency, cooperating/operating institutions and general access.

d. A protocol describing the initial and the long-term relationship among the NRC, USGS and cooperating/operating institutions.

3. After the Plan has been agreed to by the USGS and the NRC, the NRC will provide to the USGS the sum of $500 thousand in Fiscal Year 1987, and the sum of $900 thousand in each of the Fiscal Years 1988, 1989, 1990, 1991, and 1992. These funds will be used exclusively to acquire the permanent equipment, including operating software, necessary to establish the new network.

4. The USGS shall assume full responsibility for the operation of the new stations as they are installed.

5. Progress shall be jointly reviewed by the NRC and the USGS in semi-annual meetings.

6. By agreeing to these elements, the USGS does not assume responsibility for any existing seismic monitoring equipment or other related activities currently supported by the NRC through contracts or other legal instruments.

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B

Appendix B
Soil Response Program

NRC Project Manager: Jacob Philip

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APPENDIX B

SOIL RESPONSE PROGRAM

1. INTRODUCTION

The NRC geotechnical engineering staff reviews information that is presented by applicants concerning the properties and stability of soil and rock formations that may affect the safety of nuclear power plant facilities under both static and dynamic conditions. The dynamic conditions include the vibratory ground motions associated with the Safe Shutdown Earthquake (SSE). The review encompasses several specific areas: the geologic features in the vicinity of the site; the static and dynamic engineering properties of the soil and rock formations underlying the site; the responses of site soils or rocks to dynamic loading; the liquefaction potential of the soil and its consequences, including the resulting settlement of structures; the change in groundwater conditions; and the piezometric pressure in all critical strata as they affect the loading and stability of foundation materials.

The Office of Nuclear Regulatory Research (RES) has been sponsoring research to develop state-of-the-art information in the areas of earthquake-induced soil liquefaction and settlement. These latter soil instabilities are the result of either permanent or transient reduction of the undrained shear strength of the foundation soil caused by excess porewater pressures or disturbance of the soil structure accompanying cyclic earthquake loading.

The fundamental regulatory issue that needs to be addressed by the research concerns the seismic stability of the nuclear power plant foundation soils when subject to seismic loads up to or greater than the SSE. The issue takes on added importance following the United States Geological Survey (USGS) ruling in November 1982. The USGS noted that it has not been able to associate the Charleston earthquake of 1886 with a known geological structure. There is a probability, however very low, that the level of ground motion associated with a Charleston-sized earthquake could occur elsewhere on the Atlantic seaboard.

Also, in the recent past, high-amplitude, high-frequency accelerations of limited duration were recorded in several eastern seaboard locations, e.g., New Brunswick, Monticello Reservoir, and in the vicinity of the Perry Nuclear Power Plant. Since many nuclear power plants are founded on soil, the stability of their structures, systems, and components, subject to possible foundation soil liquefaction and seismic settlement, becomes a matter of concern.

The current simplified assumption of earthquake loading in a soil mass is that the earthquake induces oscillating shear stresses and strains from the horizontal components of motion with the primary effect of inertia loading on the vertical component of motion. Soil response to earthquake loading, however, is complex and nonlinear. Depending on soil type and site parameters, soil may experience liquefaction and/or settlement. Methodologies for analysis or prediction of liquefaction and settlement must take into consideration the major variables influencing this behavior. These variables include soil type, relative density, nonlinear pore pressure effects, the magnitude and intensity of the dynamic loads, etc.

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Most dynamic analysis techniques presently in use for determining soil response to earthquakes are based on total stress, which at any point on a section through saturated soil is the summation of the porewater pressure and the effective pressure due to intergranular stress. Deformation of soil is, however, controlled by effective stress. Until recently, no dynamic effective stress analysis technique existed for lack of a model to predict porewater pressures developed by seismic loading. As a result, soil settlement and liquefaction could not be accurately predicted. The RES-sponsored research is focused on establishing a data base on soil liquefaction and settlement and improving the analysis techniques by using dynamic effective stress models to predict soil response to seismic motion. The models are currently being validated by analyzing data generated from laboratory centrifuge testing of the behavior of structures simulating nuclear power plants. Field validation of the analytical models, in particular using data from NRC's cooperative programs with the Electric Power Research Institute (EPRI) at Lotung, Taiwan, and the HDR program with the Federal Republic of Germany, is contemplated in the future.

2. BACKGROUND

Three research projects address the uncertainties inherent in modeling the major variables influencing soil response to earthquake motions, such as nonlinear pore pressure generation and dissipation, strain softening from reduced effective stress, and decrease in shear modulus. A closely related research project on the state of the art on earthquake-induced liquefaction in soils, funded by NRC, was completed earlier. Also completed was a review of the state of knowledge of the causes and effects of liquefaction of soils during earthquakes. This program was partly funded by the NRC.

Seismic probabilistic risk assessments (PRAs) are increasingly being applied to clarify safety issues for nuclear power plants. Presently there are no NRC research programs for the development of probabilistic methodologies in geotechnical engineering for incorporation in seismic PRAs. Discussions are under way to initiate research in this area. Cooperative research programs with NRC participation to evaluate, among other items, current design criteria and the adequacy of models to predict soil-structure-interaction effects are currently in progress. The organizations involved in these programs include EPRI (and the Taiwan Power Company (Taipower)) and the Federal Ministry for Research and Technology (BMFT) in the Federal Republic of Germany.

A discussion of the geotechnical engineering research programs currently being conducted, those being contemplated, and those completed within the NRC follows. Also described is related research outside the NRC and cooperative programs in which NRC is a participant.

2.1 Dynamic Soil Settlement Programs

In addressing the issue of soil response to earthquakes, NRC has used the experience of the U.S. Army Corps of Engineers Waterways Experiment Station at Vicksburg, Mississippi. The Corps of Engineers has extensive experience in both analytical and experimental techniques for evaluating the effects of soil response to seismic loads. In the first phase of the soil settlement research program (completed in June 1983), various available models for modeling

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foundation settlement due to earthquakes were described and evaluated (NUREG/CR-3380). The study recommended the settlement model formulated by Professor L. Finn of the University of British Columbia as the most complete and directly formulated methodology to predict seismic settlement.

Most settlement models, including Finn's, require input parameters obtained from cyclic simple shear tests. Since data from these tests are not usually readily available, use of cyclic triaxial test data in the various models was developed in Phase II of the research. In Phase III of the program, centrifuge tests have been conducted with earthquake simulation for conditions of level ground and embedded structures simulating nuclear power plant buildings to generate equivalent response data for analysis. The centrifuge tests were conducted at Cambridge University, Cambridge, England. Internal measurements were made by the use of accelerometers, porewater pressure transducers, and displacement transducers. Realistic prototypes of in situ gravity loading stress fields were obtained in the free field as well as beneath the model structures. The earthquake excitations were conducted in both increasing and decreasing order to determine shear strain history effects. Both dry and saturated specimens were tested. In addition, engineering properties of the sand used in the centrifuge were determined. The tests included cyclic and conventional triaxial loading tests, cyclic simple shear tests, and resonant column or torsional testing. The research will establish an earthquake response data base that is unique. It will result in a nonlinear, 2-D, and soil-structure-interaction dynamic effective stress analysis methodology verified by comparisons with centrifuge test data. Development of a 3-D model by extending the formulations of the 2-D model and conducting some additional centrifuge tests is planned as a logical extension of the present work.

2.2 Liquefaction at Waterfront Structures

This research program is a joint effort by the Massachusetts Institute of Technology, Cambridge, Massachusetts, and the University of Cambridge, England, conducted through the National Science Foundation (NSF). NRC funds the program through an interagency agreement with NSF.

The research is concerned with the analysis of stability failure resulting from the liquefaction of saturated sand. In general such failures, which could occur at waterfront structures such as cooling water intake structures at nuclear power plant sites, involve the redistribution of pore pressures and localized volume change within the mass of sand during and following an earthquake. The result can be a delayed failure occurring sometime after the cessation of earthquake ground shaking.

Despite the progress made in understanding the phenomenon of liquefaction and in the analysis of sites and earth structures for possible susceptibility to liquefaction, the development of stability failure--especially delayed failures--is still a poorly understood problem. The phenomenon was observed quite dramatically in centrifuge tests (conducted under the program described in Section 2.1) and in numerous seawall failures and was emphasized in the proceedings of a number of workshops on liquefaction in 1985.

The phenomenon of delayed stability failure is illustrated by two examples on Figure 1. Figure 1a shows an anchored structure at a waterfront

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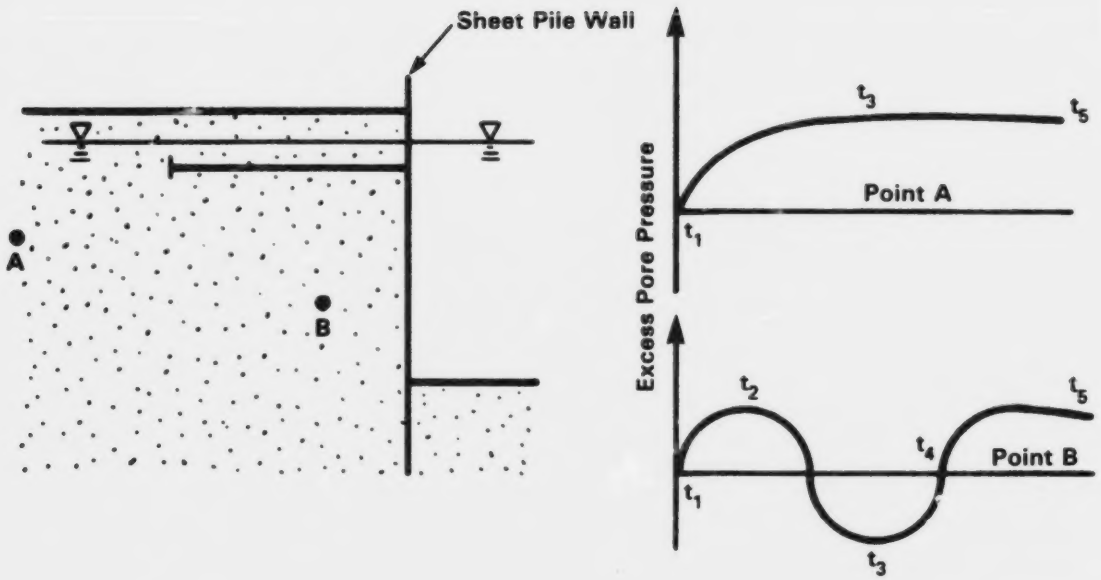
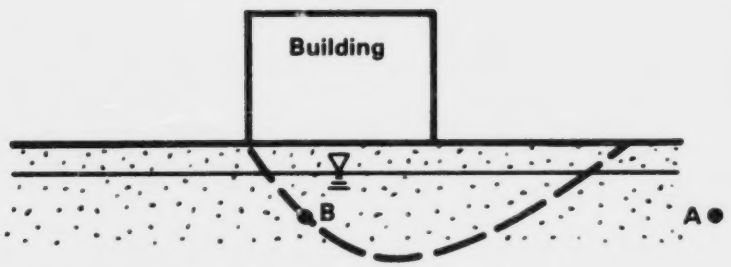


1a. Waterfront Structures such as Cooling Water Intakes. (Ground shaking begins at time t_1 and continues until t_3. At t_2, shear failure develops and sand at B dilates. By t_4, water is flowing to point B from point A well away from the wall. The porewater pressure at B increases, and a shear failure may occur. Eventually (t_5), the excess pore pressure dissipates, and stability increases again.)



1b. Buildings such as Nuclear Power Plant Structures. (Building on saturated sand. The pore pressure diagrams above apply here also.)

Figure 1. Illustration of Delayed Liquefaction Failures.

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location. Earthquake shaking causes positive pore pressure to be induced in the saturated sand behind the structure decreasing its stability. However, as a shear failure begins to develop, the sand at point B dilates, and the excess pressures at this point stop increasing and may even decrease--thus keeping the wall in equilibrium. Now there is a gradient toward point B; water starts to flow to this point, allowing the pore pressure at this point to increase. Thus, the shear resistance at point B decreases with time, and shear failure may finally occur. Eventually, the excess pore pressures will dissipate and, if a failure has not already occurred, stability will begin to increase again.

Figure 1b depicts a building founded upon a saturated sand. The same patterns of changes in pore pressure and stability versus time apply here. Now point B is located beneath the building on the potential failure surface. As the pore pressure increases, the building can experience settlement whenever the bearing capacity of the soil becomes less than the load of the building.

2.3 Seismic Wave Propagation in Soil and Rock

The effects of soil overburden on seismic wave propagation from bedrock are basically unknown. Theoretical analyses use assumptions that have not been validated with field tests. Direct measurements of motions as seismic waves passing through overburden soil are very rare, and there is a critical lack of this type of data for analysis verification. The seismic motions in soil need to be accurately modeled and known for analyses of soil behavior such as liquefaction and dynamic settlement and for structural response.

To acquire data on seismic wave propagation in both crystalline bedrock and overlying soil, NRC is a participant in a program to drill and instrument several 100- to 600-foot holes near Anza, California. The soil depth is appoximately 100 feet. Anza is located in a highly active seismic area and could be the site of a magnitude 6.5 or greater earthquake.

2.4 State of the Art on Earthquake-Induced Liquefaction in Soils

This research was an NRC-funded project conducted by the Corps of Engineers and completed in October 1985 (NUREG/CR-4430, "Current Methodologies for Assessing the Potential for Earthquake Induced Liquefaction in Soils"). The report presents a survey of current methods of evaluating the potential for seismically induced liquefaction in soils, with emphasis on screening procedures and simplified methods of analysis. Methods of detailed analysis were dealt with by providing reference in the literature. Screening procedures used worst case assumptions or simplified methods that established with a satisfactory degree of certainty that a particular site or soil deposit is safe against failure due to liquefaction, or conversely, that it is clearly unsatisfactory.

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To summarize, the knowledge of liquefaction behavior of clean sands has reached a point where the factors controlling liquefaction, if not the underlying mechanisms, can be specified with a reasonable degree of confidence. However, new information on occurrences of liquefaction leads to the conclusion that clays of low plasticity and gravels are not immune to the effects of seismic shaking as previously believed. More work is required in this area.

The present practice for direct measurement of liquefaction potential is of necessity dominated by the Standard Penetration Test (SPT) because of the availability of an SPT data base for correlation with observations of field performance--a data base that is not yet available for any other in situ test. For the future, various configurations of the cone penetrometer device seem to be the most promising method for a variety of site conditions, whether pertaining to existing or proposed foundations.

2.5 Workshop on Reducing Earthquake Hazard from Liquefaction of Soils

In conjunction with the workshop, a report ("Liquefaction of Soils During Earthquakes," National Academy Press, Washington, D.C., 1985) was published.

This report reviews the state of knowledge of the causes and effects of liquefaction of soils during earthquakes, documents the state of the art of analysis for safety from liquefaction, and recommends future directions for liquefaction research. It is a product of a workshop held in Dedham, Massachusetts, on March 28-30, 1985, at which liquefaction specialists from the United States, Japan, Canada, and the United Kingdom came together to discuss present knowledge and agree on directions for the future. The workshop was conducted in response to requests from the National Science Foundation and NRC.

The report emphasizes the role of porewater pressure buildup in the soil during earthquake motions as the main cause of liquefaction. The factors affecting the porewater pressure buildup include the amplitude of the oscillatory straining; the past history of soil stressing; the size, shape, and gradation of particles; the confining pressure acting on the soil; the age of the deposit; the fabric of the soil; and the overconsolidation ratio. Saturated granular soils without cohesive fines (i.e., some silts, sands, and even gravels) are most susceptible to the buildup of pore pressure. However, the greater the content of clays and other fine particles contributing plasticity, the less the susceptibility to pore pressure buildup and the lower the potential for seismically induced liquefaction.

The adverse effects of liquefaction are discussed in the report. Some are catastrophic such as flow failures of slopes or earthworks, settling and tipping of buildings and piers of bridges, and total or partial collapse of retaining walls. Others are less dramatic such as lateral spreading of slightly inclined ground, large deformations of the ground surface, etc.

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The report details the use of charts for evaluating liquefaction potential based on observed field performance from SPT and cone penetrometer testing (CPT). It discusses the relevant aspects and capabilities of numerical methods for evaluating liquefaction potential and settlement. The codes discussed include the widely used equivalent linear total stress analysis model SHAKE, the effective stress analysis code DESRA, and the 2-D fully coupled program TARA. The latter two codes were developed by Professor L. Finn and are being validated by analysis of data from the centrifuge experiments (discussed under Section 2.1 above).

Despite the important progress made in understanding liquefaction, the report lists important additional research and development work in dealing with seismically induced liquefaction and settlement. These include:

1. Instrumentation of sites where the probability of liquefaction is high.

2. Study of gravels and cohesive soils with low plasticity.

3. Improvement of in situ methods for evaluating liquefaction potential.

4. Determination of in situ state of stress in soil prior to earthquake occurrence.

5. Use of explosion-generated stress waves to study liquefaction.

2.6 Geotechnical Engineering Issues for Seismic PRAs

Seismic probabilistic risk assessments are increasingly being applied to clarify safety issues for nuclear power plants. Presently there are no NRC research programs for the development of probabilistic methodologies in geotechnical engineering for incorporation in seismic PRAs. There is a critical research need in this area in order to enhance the confidence in seismic PRA outcomes.

In general, three aspects are considered and technical information is required in three areas as inputs to a seismic PRA. These are:

1 The seismic hazard at the site (hazards analysis).

2. The level and parameters of the hazard that can cause vital nuclear power plant structures, systems, and components to fail (fragility analysis).

3. The description of failure scenarios (fault trees/event trees).

In the hazards analysis, the ground-motion-prediction models generally do not adjust for the local site condition effects in the estimate of the hazard at the site. Uncertainties in the characteristics and nature of wave propagation in soil materials make any adjustment open to question.

The susceptibility of the nuclear power plant to seismic excitation is determined by the plant fragility analysis. This analysis requires a response analysis of the soil-structure systems to establish, among other things, the base motion of component support. For the soil-structure-interaction analysis, the effect of liquefaction, settlement, and basemat uplift are typically not

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modeled in a seismic PRA fragility analysis. Liquefaction and seismic settlement are highly nonlinear phenomena. The level of excitation, site properties, and foundation geometry influence the magnitude of uplift, which in turn significantly modifies the floor response spectra. Typical soil-structure-interaction analysis based on linear analysis, including that used for seismic PRAs, cannot directly model basemat uplift. When uplift is found to be important, it is treated outside the direct methodology. These methods are in need of validation. The objective of validation research is to obtain information that can be used by NRC to enhance confidence in seismic PRA outcomes.

2.7 In Situ Methods for Prediction of Soil Liquefaction Potential and Settlement

A promising in situ technique for the study of liquefaction potential of soil deposits has been developed by the University of Texas, Austin, Texas. The technique uses low- and high-frequency Raleigh waves and was employed at several liquefied soil sites in the Imperial Valley, California, by the university for the USGS. By using a fast Fourier transform and spectral analysis, Raleigh wave velocity for each frequency is calculated. With inversion, shear wave velocity, shear modulus, and layering of the media are determined. The shear wave velocity profile of the subsurface strata is then correlated with varying levels of earthquake accelerations from dynamic analysis to predict the potential for liquefaction. This method has been found to be an accurate measure of shear wave velocity to depths of up to 40 feet.

2.8 Probabilistic Geotechnical Engineering Research at University of British Columbia, Canada

Computer programs have been developed at the University of British Columbia, Canada, for the computation of the probability of seismically induced liquefaction. The technique combines Seed's "simplified method," which is deterministic in nature, with Cornell's probabilistic approach to evaluation of expected seismic ground motions. The main benefits to be derived from the use of the programs are the quantification of the liquefaction hazard levels and as an aid to judgment in those areas where the degree of risk posed by different environmental hazards may be unclear.

2.9 EPRI/NRC Cooperative Program at Lotung, Taiwan

EPRI has constructed a model about one-fourth the size of a concrete containment in a seismically active area in Taiwan. Argonne National Laboratory is the NRC coordinator for this effort. Instruments installed by EPRI in the model, and in vertical and horizontal arrays in its vicinity, record responses to earthquakes over a 5-year period. Taiwan Electric Power (Taipower) has the responsibility to monitor the instruments. NRC has performed low-level vibration tests to define the dynamic characteristics of the soil-structure system in an as-built condition before the system was subjected to a strong-motion event. A second series of tests were performed on the completed structure. Since the model was completed in October 1985, the EPRI Lotung site has recorded more than a dozen seismic events. Blind analytical predictions are currently being performed by different analysts using various techniques. The results of this program will be valuable in providing validated analytical models to predict soil-structure-interaction effects for United States recorded earthquakes and in comparing predictions with observations.

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2.10 Government of Federal Republic of Germany (FRG)/NRC Cooperative Program at HDR Facility in FRG

The HDR (Heissdampfreaktor) Test Facility in Kahl/Main, FRG, has been used since 1975 to perform vibrational, thermal-hydraulic, blowdown and other experiments related to the design and safety of nuclear power plants. During the first phase of the HDR program, the building and equipment were subjected to many low- and medium-level mechanical excitations. In the second phase, high-level shaker tests, designated SHAG tests, were performed at the HDR in June and July 1986. Their purpose was to investigate full-scale structural response, soil-structure interaction, and piping and equipment response under strong excitation conditions. The purpose of the experiment is to use the SHAG tests to verify and validate calculational procedures and analysis methods.

The SHAG tests were planned to provide the maximum possible loading for the HDR soil-structure system and piping without inducing global soil-structure failure that would endanger the integrity of the containment. As it turns out, substantial amounts of energy were transferred to the surrounding soil, particularly during experiments challenging the rocking mode. High accelerations were measured in the soil, and there was cracking of soil away from the building and separation at the soil-structure interface and soil subsidence.

Pretest and blind posttest calculational predictions were and are being performed for many aspects of the SHAG tests. These calculations will be compared with observations in the SHAG tests to verify and validate calculational procedures and analysis methods. NRC participation in the program is coordinated through Argonne National Laboratory.

3. PROGRAM PLAN

The program plan to resolve the technical issues described in the preceding section is presented here. The research to be accomplished and project schedules are described. Where relevant, interactions of the subject research with other elements of research within and outside of NRC are discussed. Schedules for future contemplated research are approximate.

As discussed before, the RES-sponsored research on soil response is focused on establishing a data base on soil liquefaction and settlement and improving the analytical techniques of predicting soil response to earthquake. Three research projects currently in progress address this need. A closely related research project planned for the future concerns geotechnical engineering issues for seismic PRAs.

3.1 Dynamic Soil Settlement Research

1. Research Accomplished and in Process

A total of 11 centrifuge tests using 118 earthquake simulations has been conducted at Cambridge University, England. Approximately 1,500 response records of a data base have been acquired. Tests conducted included dry and saturated soil models with and without a form of structural loading either on the surface or embedded. Embedded structures were both plain strain two-dimensional (2-D) and three-dimensional (3-D). The soil foundation material used in all tests was Leighton Buzzard Sand.

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The work has resulted in a unique earthquake response data base. It has also resulted in a verified nonlinear, 2-D, and soil-structure-interaction dynamic effective stress methodology while computing settlement and porewater pressure histories, in addition to motions for earthquake excitation. Both dry and saturated soil conditions can be treated. The methodology is rigorous and input parameters can be determined from standard field and cyclic triaxial tests.

Analysis of the centrifuge test result is in progress and is expected to be completed by the second quarter of 1987. The analysis will provide comparisons of the theoretical calculations with laboratory-controlled physical performance tests and hence validate the settlement models developed by L. Finn.

Preliminary results indicate that there are differences in the dynamic effect predicted by Finn's 2-D and 3-D interaction models. The results show a zone around the simulated nuclear power plant structure where foundation loosening occurs, probably because of differences in the response of soil and structure during the earthquake. The results also show deficiencies in the widely used 1-D SHAKE code and the 2-D FLUSH code to predict seismic motions transmitted through the soil and structure. These deficiencies are attributed mainly to the porewater pressure effect, not included in these codes.

2. Continuing Research

The study above is to be continued with the development of the 2-D model into 3-D for analysis of the interactive effects and differential responses at sites containing complex interconnected structures such as those at nuclear power plants. Development of the 3-D model will be done by extending the formulations of the 2-D model and building on the analyses and tests previously conducted in this study.

The centrifuge tests conducted to date were not continued to induce catastrophic liquefaction failure. In the continuing work, three catastrophic centrifuge tests will be conducted to simulate liquefaction and/or flow type failure behavior similar to the phenomenon that has been observed in the field and that is believed to occur.

3. Integration and Relationship With Other Research

a. The characteristics of the input motions for the validated dynamic effective stress models (from this research program) can be better defined from the results of the Anza, California research program (see Section 2.3).

b. The soil response data from the NRC/EPRI Cooperative Program at Lotung, Taiwan (see Section 2.9) and the HDR program, FRG (see Section 2.10) can be tested against the centrifuge earthquake response data from this program. This would be a valuable laboratory complement to the field data analysis. Alternatively, the field tests at both sites can be modeled in the centrifuge and predictions on the soil-structure response calculated by the validated models from this program and then compared with field observations.

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4. Products

a. Verified and validated nonlinear, 2-D, soil-structure-interactive dynamic effective stress model that computes seismic settlement, porewater pressure histories, and accelerations in the soil and structure (1987-1988).

b. Verified and validated nonlinear, 3-D soil-structure-interactive dynamic effective stress model that computes seismic settlement, porewater pressure histories, and accelerations (1988-1990). It accounts for the differential responses of sites containing structures with various geometries, loading, and interconnections.

3.2 Liquefaction at Waterfront Structures

1. Research Accomplished and Being Done

Two series of tests will be carried out using the 15g-ton centrifuge at the Massachusetts Institute of Technology. These tests are designed to study the effect of initial void ratio upon the development of liquefaction-like failures.

In addition, centrifuge modeled bearing capacity tests will be conducted and will investigate the influence of (a) bearing stress of a model structure, (b) the ratio of width of the structure to the thickness of its sand foundation, (c) the ratio of the height of the structure to its width, and (d) the initial void ratio of the sand on bearing capacity failure due to initial liquefaction. Other tests include centrifuge testing at the University of Cambridge on realistic waterfront structural walls such as at intake structures at nuclear power plants. The settlement of the surcharge loads will be monitored in the centrifuge experiment as well as movements of the wall and pore pressures and accelerations at a number of points within the sand backfill against the wall.

The emphasis in this research will be upon interpretation of the general features of the observed behavior so as to deduce conclusions of engineering significance. It will lead to a better understanding and help in reducing the probability of stability failures due to delayed liquefaction effects at waterfront structures.

2. Integration and Relationship With Other Research

Comparisons of the observed behavior from the testing program may be made with predictions from validated computer codes developed in the soil settlement research program (see Section 2.1).

3.3 Seismic Wave Propagation Research

1. Research Planned

The research plan reported in this section covers the drilling, soil sampling, and testing to be conducted for NRC by the Corps of Engineers. Details of other aspects of this program are discussed in Appendix A, Seismotectonic Plan. Data from the research program will be disseminated to all participants of the program (NRC, Commissariat a l'Energie Atomique, France (CEA),

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USGS, COE) for analysis using different numerical methods. Details of the program plan follow:

a. Drill three boreholes at 10-15 feet spacings and place 3-in I.D. casings in the overburden soil and 10 feet into bedrock. In one of the boreholes, three undisturbed soil samples are to be retrieved at three locations, for a total of nine undisturbed soil samples. Continuous SPT sampling is to be done in one borehole.

b. Crosshole shear wave propagation tests at depth increment of 3 to 5 feet are to be conducted in the three boreholes. Surface wave (Raleigh waves) techniques will be conducted to determine lateral subsurface variations.

c. Hole deviation surveys will be conducted in the five large-diameter boreholes (6 to 7 inches).

d. Laboratory tests will be conducted on the undisturbed and SPT soil samples. Future Corps of Engineers work will involve analysis of the data generated at the site.

2. Integration and Relationship With Other Research

a. The research complements the seismotectonic program relative to the study of seismic strong ground motion.

b. Results from this program will help to better define the input motions required for the research described under Sections 2.1 and 2.2.

c. Results from this program will help to provide more accurate calculational predictions of the soil-structure interaction being observed in field experiments at Lotung, Taiwan, and at the HDR, Federal Republic of Germany.

3.4 Geotechnical Engineering Issues for Seismic PRAs

1. Research Contemplated

The research program on geotechnical-engineering-related aspects of PRAs involves two steps.

a. The first involves the identification and/or development of the most appropriate methodology for quantitatively assessing the probability of the failure of foundations, slopes, embankment, dams, etc., when these facilities are subjected to a seismic event. Some of the geotechnical engineering parameters to be considered in the probabilistic analysis include the adequacy of site exploration programs, the static and dynamic properties of the foundation and backfill materials, the potential for subsidence, settlement, and liquefaction of

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foundation soils, the question of problem (e.g., expansive or dispersive) soils, etc.

b. In the second stage of the research, the impact of the geotechnical parameters described above on the hazard analysis and plant fragility analysis for seismic PRAs is to be determined. Uncertainties in the hazard analysis arise from poor understanding of several factors, including site soil characteristics and wave propagation through the earth's crust. Also, typically, soil failure of liquefaction, settlement, and basemat uplift are not modeled for fragility estimates in seismic PRAs and their significance needs to be evaluated. Validation, using test data from specific laboratory and field experiments as well as measurements obtained from earthquakes or other natural environments will form part of the research effort in the areas of geotechnical engineering impacts to plant response and fragility. The goal of the research is to improve the predictive capability and enhance the understanding of the outcomes of seismic PRAs.

2. Integration and Relationship With Other Research

This research effort complements other PRA research described in Appendix E. The geotechnical engineering aspects of seismic PRAs form part of the studies on the seismic response of the soil-structure system. This system acts as transmitter and filter of vibratory motion to the safety systems whose fragility is of interest. The structure system is intended to perform its design function during and after any earthquake.

4. REGULATORY APPLICATION

The results from the program on the validation of dynamic effective stress models will be used by the staff to more accurately predict seismic liquefaction and settlement of nuclear power plant structures, systems, and components. The program on the effects of soil overburden on propagation of seismic waves from bedrock will better define deconvolution methods for determining the loads at foundation level and the spatial variation of the seismic loading in an earthquake. Probabilistic methodologies in geotechnical engineering will vastly improve the current seismic wave attenuation models used in the hazard analysis for seismic PRAs and make it more site specific. It will also better define the susceptibility of the nuclear power plant structures, systems, and components to seismic excitation due to various soil failure models; in effect it will lead to better estimating of plant fragility. The program will enhance the confidence in seismic PRA outcomes. The studies on delayed stability failures at waterfront structures will improve the understanding of this phenomenon. The analytical and experimental information provided by the entire program, in summary, will be used to quantify the adequacy of the seismic design margins and provide improved confidence in the outcome of seismic PRAs. NRR standard review plans will have to be revised based on the results of the program and new regulatory guides developed.

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C

Appendix C
Seismic Category I Structures Program

NRC Project Manager: Roger M. Kenneally

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I. PROGRAM INTRODUCTION

The issues of safety as related to nuclear power plant Category I buildings have, in the past several years, shifted from the design of new buildings to issues related to operating plants. The principal issues related to operating plants center around aging effects and changing criteria. The Seismic Category I Structures Program was established to address the licensing issue: can existing facilities continue to operate in light of more demanding seismic criteria than those considered in the initial design?

The principal users of the research results from the Seismic Category I Structures Program will be the Nuclear Reactor Regulation (NRR) Division of Engineering and System Technology. The needs identified by the staff of this division are:

1. understanding the behavior of Category I structures (other than the containment) subjected to earthquake motions beyond design. The behavior of the structure to load magnitudes such that both elastic and inelastic response occurs is of interest;

2. identify the changes in floor response spectra at various magnitudes and duration of input loading; and

3. identify the changes in damping associated with the various magnitudes and duration of input loading.

Based on the licensing issue and the user office needs, the objectives of the Seismic Category I Structures Program are:

1. to address the seismic response of reinforced concrete Category I structures other than containments;

2. to develop experimental data for determining the sensitivity of structural behavior in the elastic and inelastic response range of Category I structures to variations in configuration, design practices and earthquake loading;

3. to develop experimental data to enable validation of computer programs used to predict the behavior of Category I structures during earthquake motions that cause elastic and inelastic response;

4. to identify floor response spectra changes that occur during earthquake motions that cause elastic and inelastic structural response;

5. to develop a method for representing damping in the inelastic range, and demonstrate how this damping changes when structural response goes from the elastic to the inelastic ranges; and

6. to assess how shifts in structural frequency affects plant risk.

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The Seismic Category I Structures Program is a combined experimental/analytical program with the initial work heavily emphasizing the experimental aspects to develop a good data base. In the latter phases of this program the emphasis will shift toward more analytical development to determine the sensitivity of significant geometry or configurational changes and plant risk. However, a limited number of experiments will be performed to support analytical development.

The Seismic Category I Structures Program has two major elements: the behavior of reinforced concrete noncontainment structures, and the effects of structural response on plant risk. The research program addressing each of these areas is described below.

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II. BEHAVIOR OF REINFORCED CONCRETE NONCONTAINMENT STRUCTURES

This research being performed at the Los Alamos National Laboratory (LANL) is focused on the first five objectives stated in the Introduction (Section I). Data from this research will be used to determine how changes in structural response affect plant risk (Section III).

A. Complementary Domestic and Foreign Research

The class of structures being investigated, that is, Seismic Category I structures exclusive of containment are usually low aspect ratio shear wall structures. In this class of structures the shear wall is the principal lateral load-carrying structural element. There are few structural frames acting in conjunction with the shear wall. Also, there are very few penetrations in the shear wall; hence there are few coupling beams connecting the shear walls. Finally, as implied by the low aspect ratio description these buildings are short and squat in nature.

1. Domestic Research

Seismic investigations to understand structural behavior, and develop design criteria for commercial multi-story frame structures that may or may not include shear walls have been conducted at many different institutions. The greatest number of investigations have been strictly analytical; however, a significant number of experimental investigations have also been conducted. Because a seismic Category I structure is shear-wall dominated, only a few of the investigations have applicability to the needs addressed by this program. For example, Reference 1 lists almost 600 articles pertaining to the design, analysis, construction and testing of shear walls and shear wall structures through 1974. However, once articles pertaining solely to high-rise structures, coupled shear walls and frame-wall systems are eliminated there are very few articles related to the class of structures of interest in this program. There are a number of experimental investigations that have been or are being performed that have direct applicability to reinforced concrete containment buildings. The Seismic Category I Structures Program excludes consideration of containment buildings, but keeps abreast of the literature for results that can be applicable. A summary of the research performed by the major institutions that have been active in testing of reinforced concrete elements and structures is given below. Domestic and foreign research has been conducted, is currently underway, or is planned that may have applicability for determining the seismic behavior of Category I buildings is summarized below.

1.1 Construction Technology Laboratories (CTL)

The CTL, a division of Portland Cement Association (PCA), located near Skokie, Illinois, performs both analytical and experimental investigations on reinforced concrete elements and buildings. It has extensive experience in the construction and testing of model reinforced concrete structures. Of particular pertinence to this program are the CTL tests on isolated shear walls. The purpose of these investigations was to develop

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strength relationships that could be used in the design of shear walls. Eight low aspect ratio shear walls with flexural boundary elements were tested. The aspect ratio was varied between 0.25 and 1 and the amounts of flexural reinforcement were also varied. Wall thickness was 4 inches. These tests were used to assess the response of a shear wall to quasi-static load reversals. Results were compared with the design provisions of the 1971 ACI Code; the design provisions were found to be overly conservative with respect to ultimate load and alternative design guides were suggested. In addition, the reports of this work provide a thorough summary of the literature pertaining to low aspect ratio shear walls through 1972. Included in that literature search is the early work done on shear in beams and subsequently shear in deep beams and corbels that precludes but pertains to the work done on shear walls.

Further experimental work was performed by the PCA beginning in 1974. Sixteen shear walls with an aspect ratio of 2.4 and a wall thickness of 4 in., were subjected to monotonic and cyclic loading including a modified cyclic loading to simulate seismic excitation. Boundary elements were varied along with the amount of reinforcement. Failure mechanisms were identified based upon the nominal shear stress level and the walls were found to exceed the ACI 318-71 design provisions. Normal stresses were found to increase shear stiffness through aggregate interlock. Also, free vibration tests were performed on the walls to determine natural frequency and equivalent viscous damping values. These tests were performed at various times during the static loading so that the effects of cracking could be assessed. Axial forces were found to have little effect on the vibration characteristics of the structure. An empirical relationship for shear distortion versus flexural rotations was developed.

Further work done at the PCA (1980) examined the response of seven shear walls (aspect ratio = 1) with varying amounts and configurations of reinforcements. The amounts of reinforcement were shown to have little effect on the stiffness of the walls up to ultimate load. The results reported in this study were used to develop the design criterion, "Special Provisions for Walls," Section 11.10 in ACI 318-77.

1.2 University of California at Berkeley (UCB)

Both large-scale static tests and dynamic tests are conducted at UCB. A large shake table is located at UCB and is accessible to the University researchers. The frequency limit on this shaker is about 20 Hz, thus giving the shaker limited utility for the models used on this program because these model structures require excitation frequencies up to 200 Hz to fulfill the similitude requirements. The UCB has performed considerable testing related to concrete structures; however, the testing has been directed toward determining the behavior of frame buildings and has little applicability to shear wall buildings. The tests at UCB have included the load cycling of beam-column connections, earthquake loading of small masonry buildings, and earthquake loading of a 1/5 scale reinforced concrete frameshear wall building.

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1.3 University of Illinois (UI)

The UI researchers have considerable experience in the construction of reinforced concrete scale models, and have contributed their experience to this program through participation in the Technical Review Group (TRG). The UI has capabilities for both static and dynamic testing. Large load capacity for quasi-static loads exists, but the capacity of their seismic simulator is limited.

Many of their static tests results on reinforced concrete structural elements found in frame buildings have been incorporated into the ACI Building Code.

Tests that have been performed on their seismic simulator include scale models for frame buildings containing a limited number of shear walls. The correlation of analytical/experimental comparisons from these tests are used in planning our research to ensure credible results are obtained. For example, work performed at UI has supported preliminary findings that showed test structures respond to dynamic loads with a reduction in stiffness of four. The test structures used in UI investigation were, however, not of similar geometry as those found in this program.

1.4 Stanford University (SU)

The work done at SU consisted of a series of 79 tests on scale model shear walls. These were static, monotonic tests of low aspect ratio shear walls with aspect ratios ranging from 0.3 to 1 and wall thickness ranging from 1 to 3 inches. The walls were attached to end columns or boundary walls and load was transferred to the shear wall through a top beam or plate. The amounts and arrangement of the reinforcement were varied including some tests without reinforcement. Other variables examined include column size and reinforcements, effects of opening, effects of vertical loads, effects of floor slabs and end walls. Results showed that a simple strength-of-materials approach for determining stiffness was adequate during the uncracked response of the wall. Empirical relationships were developed for the ultimate strength and deflection of the walls. Conclusions drawn from the SU investigation include:

1. no scale effects were observed, if they were present they were within the data scatter;

2. the lower the aspect ratio, the closer the first cracking load to the ultimate load;

3. a rectangular reinforcing pattern was more effective than a diagonal pattern;

4. horizontal steel was ineffective in resisting shear;

5. when the bearing load was less than the total shear force, the effects of the normal force on stiffness were negligible;

6. strengths increased with increased loading rate.

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1.5 Massachusetts Institute of Technology (MIT)

At MIT investigators statically tested 12 shear walls similar in configuration to the ones tested at Stanford and compared the results to tests of frames with shear walls. The shear walls had an aspect ratio of 0.65 and a wall thickness of 1.75 in. Loading was monotonic and the amount of reinforcement was varied. Analytical predictions of the load deflection curve based on lattice analogy were found to be in good agreement with the experimental results.

Antebi (Ph.D. thesis MIT 1964) reports further on the work done at MIT including experimental results from some 19 static tests and 41 dynamic tests (impulsive loading). The objective of this work was to study the behavior of shear walls under static and dynamic loads and to demonstrate the use of scale models for dynamic testing. The test specimens were purposely constructed of similar geometry to the specimens tested at Stanford. The aspect ratios for 54 of the specimens was 0.60, and the remaining six specimens had an aspect ratio of 0.30. Wall thickness ranged from 1 to 3 inches. Reinforcement was varied as was the load pulse for the dynamic testing. Also, 76 1/10 scale models of the above shear walls were tested in a similar manner both statically and dynamically. Additional tests were made on other of these models at an aspect ratio of 0.23. Results presented showed the effects of different variable (aspect ratio, amount of reinforcement, load pulse duration) on the ultimate strength of the shear wall. Scale effects were noted both in cylinder testing and in actual shear wall testing; however, the models usually predicted results within 20% of those measured in the prototype. An empirical formula for the static ultimate strength as a function of aspect ratio, amount of reinforcement and wall thickness was developed. No dynamic properties (natural frequency, damping) of the structure other than ultimate load were reported.

In conjunction with the shear wall tests, tests were also performed to examine the dynamic bond strength between the reinforcement and concrete. Bond strength was shown to increase during dynamic loads and failure of the steel was found to be more likely than loss of bond for all but short bond lengths. It was also noted that progressive bond failure and large slip may be expected from large repeated dynamic loads.

Although extensive testing of shear walls with similar aspect ratios was performed, the geometry of the test specimens were in general not similar to Seismic Category I Structures since the Seismic Category I Structures do not contain reinforced concrete frames. Also, the impulsive loading used in the dynamic tests is not similar to dynamic loads induced by seismic excitation.

1.6 Lawrence Livermore National Laboratory (LLNL)

LLNL has carried out analytical studies on the seismic fragility of reinforced concrete structures.

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In review of work pertinent to the seismic response of nuclear power plant shear wall structures, LLNL identifies stiffness as the most significant uncertainty in the response of these structures particularly at relatively low stress levels. This work reports several cases where the response of actual structures to ambient vibrations have shown reductions in frequency by a factor of 2. This report also identifies areas where scale modeling could lead to erroneous results, such as shrinkage crack effects being more predominant in scale models than in actual walls. However, no doubt that differential settlements and long term effects will produce similar effects in actual structures in time.

2. Foreign Research

2.1 Japan

The Japanese have performed a large number of tests on model shear wall structures for the purpose of establishing design criteria and to show that the structures do not fail at loads less than their design loads. These model buildings had either square or circular cross sections. The reinforcement ratio was varied and either a monotonic or cyclic load applied. In addition, a large number of tests were performed on model structures with openings. The opening size, shape, and peripheral reinforcing were varied. The test results were used to establish rules for the design of prototypical buildings. The Japanese have not always tested their structures to failure, and the information reported at conferences is not always useful to support other purposes.

The Japanese have dynamically and statically tested 1/30 scale models of a prestressed concrete containment vessel and components of a reinforced concrete reactor building that included shear walls. The models were both loaded into the inelastic range. The stated purpose of these tests was to investigate the safety factor for the design load and the lateral load displacement relationship of each component. The components were models of the outer box, the inner box, and the shield wall. The principal data published were the load-deflection relationship for cycled loadings (quasi-static).

The containment vessel was tested both statically and dynamically, the dynamic loading being artificial earthquake motions applied by a shake table. Also published were results of analytical studies. Generally, where appropriate data can be compared, trends being observed in the Seismic Category I Structures Program are being confirmed by the Japanese studies.

The Japanese are currently doing or planning research that may directly complement our effort. For example, one recent publication describes a pseudodynamic method that is being used to test larger structures. In this method a dynamic analysis of the structure is used to predict the response at various locations to a given base motion. Given this response, computer controlled hydraulic actuators load the structure at various points resulting in a presumably correct relative displacement field within the structure. Such methods may be of use in our program and they are currently under study. Other publications compare test data with

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elastic analysis and put limits on the "scope of their applicability." During a recent visit to the U.S., Japanese researchers from Japanese Atomic Energy Research Institute described an elaborate new program addressing needs similar to this program's, that is, load beyond the design basis. Cooperative research is being investigated.

A better understanding of past, present and future research efforts in Japan may be obtained as part of a technical exchange agreement between the U.S. NRC and the Japan Ministry of International Trade and Industry (MITI).

2.2 New Zealand

A number of experimental studies of structures subjected to seismic loading have been conducted in New Zealand, principally by T. Paulay. Of particular interest are their experimental studies on shear walls. Their shear wall studies did not use real or scaled time earthquake motions, but used monotonic and cyclic quasi-static loading to obtain failure mode, cracking patterns, stiffness and strength degradation, and ductility. Shear wall aspect ratios, and the arrangement and amount of reinforcing steel were varied in their tests. Their tests were aimed at usual building type of walls, but if one considers their test structures as models, it is possible to relate their results to Category I buildings. The static tests on the model structures in the New Zealand tests showed the same behavior trends as observed in the Seismic Category I Structures Program.

2.3 Germany

Results from shaker tests at the Heissdampfreaktor (HDR) facility in the Federal Republic of Germany (FRG) were analyzed to aid us in future program planning and evaluation of experimental results. The HDR is a decommissioned superheated steam reactor that has been modified to serve as a test facility. In June-July 1986, the containment building was excited by a large shaker mounted on the operating floor. Due to the magnitude of the input load results from this test provided little inelastic response information on the shear walls contained in that nuclear facility. This structure's response was dominated primarily by the soil conditions at the site.

2.4 Yugoslavia

Yugoslavian investigators have been active in experimental investigations of seismic effects on nuclear plant structures. They have conducted both ambient and forced vibration tests on the KRSKO nuclear power station in an effort to determine the proper frequency range for selection and location of seismic instrumentation and to aid in analytical model verification. The results are preliminary; therefore, no conclusions as yet can be drawn from this work about the behavior of shear wall structures. Damping values and other results will be of interest when analytical modeling is complete.

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Other Yugoslavian work has reported on efforts to incorporate results from static load cycle testing of three-story shear walls into an analytical model for predicting the seismic response of multi-story shear wall structures. The success of this effort is as yet unconfirmed.

2.5 Canada

Two experimental investigations of LARSWs were reported at the 1973 World Conference on Earthquake Engineering. At McMaster University in Ontario five LARSWs were tested (A.R. = 0.5, 0.75, 1.5, wall thickness = 4 in.) while varying the amount of normal force. The loading was quasi-static and cyclic in nature. Large normal stresses (185 psi) were observed to increase the maximum load capacity, produce a more uniform distribution of cracks, decrease stiffness degradation, increase energy absorption and reduce ductility of the walls.

The most recent experimental investigation of low aspect ratio shear walls outside of the investigation being conducted at Los Alamos are currently being carried out at the University of Toronto. To date, the results from static, cyclic tests of two structures (A.R. = 0.25, 0.5, wall thickness = 3.9 in.) have been reported. The design provisions of ACI 318-83 were found to be overly conservative with respect to ultimate load capacity for the walls tested and new design provisions were suggested. A report on six other walls tested as part of this program is due out in May 1987.

3. Current State-of-the-Art Summary

Over the last thirty-five years there have been many static experimental investigations into the seismic response of shear walls and shear wall structures. These experiments have used either monotonic or cyclic loading and have been design oriented. That is, they have attempted to determine a single static load to which the wall can be designed and be expected to resist seismic loading. The current design standards in the United States that emerged from this research when applied to low aspect ratio shear walls found in nuclear power plants have been shown to be overly conservative in terms of predicting ultimate strength.

To date, the only seismic testing of low aspect ratio shear walls and shear wall structures is this work being sponsored by the NRC at the Los Alamos National Laboratory. This work is the first to investigate the dynamic properties of low aspect ratio shear walls such as natural frequency and damping and the effects of these properties on equipment attached to low aspect ratio shear wall structures.

B. Research Program Plan

1. Background and Past Accomplishments

1.1 Shear Wall Tests

In recognition of the increasing need for research to support work on seismic related issues within the USNRC, the Seismic Category I Structures

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Program began in FY 1980. The first task was an extensive literature survey on research activities applicable to or related to Category I structures. Major A/E's of nuclear power plants were contacted and a number of general drawings on different power plants were obtained. From this information, an initial program plan was developed. The initial program plan was developed with foreknowledge that scale model testing of reinforced concrete structures is a controversial issue in the civil engineering community, particularly when the structures are loaded into the inelastic range. A Technical Review Group (TRG) composed of nationally recognized experts was assembled to aid in the planning and to comment on the progress and direction of the program. No major revisions to the initial program plan were made as a result of the first TRG and NRC staff review and the program plan was published (Ref. 2).

Category I structures are constructed mainly from low aspect ratio shear walls as opposed to structural elements whose predominant behavior is governed by bending. Thus, the first experimental tests at Los Alamos were carried out on isolated model shear wall structures. Static tests were conducted to obtain strengths and load-deflection behavior. Vibration (sine-sweep) tests were then conducted to obtain natural frequencies and equivalent viscous damping values. The results of the vibration tests were inconsistent, and it was concluded that traditional sine-sweep tests at measured load levels on reinforced concrete structures tend to overfatigue the structure resulting in confusing data and should be avoided. Thereafter, all dynamic tests used either a recorded or a computer generated accelerogram as the base input motion.

Both the static and seismic tests using the isolated shear wall structure (about 1/30 scale) indicated that the initial stiffness was significantly less than the stiffness computed assuming an uncracked concrete cross section. It should be noted that these stiffness values are at loads that correspond to 0.2 g peak applied acceleration value or better on a prototype structure.

The initial program plan called for two different scale model sizes of isolated walls to demonstrate scaling to be followed by tests on three-dimensional box-like structures. Upon reviewing the initial results the LANL staff and TRG recommended, and NRC staff approved, that the scalability demonstration should be carried out using box-like structures. Thus, using all the information found (stiffness, damping and inelastic behavior) and the testing and modeling technology that was obtained from the isolated shear wall test phase, a revised program plan was developed incorporating new (current) user office needs. This test plan was directed primarily at the use of box-like structural models.

1.2 Model Building Tests

1.2.1 Building Response

The actual seismic testing of the box-shaped test structures commenced in FY 1983. Quasi-static loads, both monotonic and cyclic, were applied parallel to the long (longitudinal) direction and to the short (transverse) direction of the box-shaped test structures. The static tests yielded

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load-deflection information (stiffness, "yield" point, inelastic behavior, ultimate load-carrying capacity and failure mode) on these structures. Ultimate failure of the test occurred at the base (foundation) and wall interface. The concrete developed a penetrating crack around the model building perimeter. The same basic failure mode was observed in the isolated shear wall tests.

Seismic tests were conducted on one story box-shaped model structures to obtain their fundamental frequencies and to observe their general behavior (crack patterns, frequency shifts, peak responses, damping, etc.). These seismic tests also showed the reduced initial stiffness over the computed uncracked cross sectional value and large equivalent viscous damping values that were observed in the isolated shear wall tests.

To verify that the scaling relationships could be used to translate test results to different size structures and to obtain general structural behavior, a 1/30 scale (one-inch wall) and two 1/10 scale (three-inch wall) two-story model Diesel Generator Building structures were seismically tested. The first 1/30 scale model structure was tested to aid in the development of the test program for the 1/10 scale structures. After the first 1/10 scale model test, additional 1/30 scale models were tested in a manner similar to the 1/10 scale model. Another 1/10 scale model test was conducted during FY 1984. The results to date indicate that the scaling relationships were adequate to predict the behavior of these modeled structures.

To illustrate this point, Fig. 1 shows the data taken from tests on three 1/30 scale model Diesel Generator Buildings (3D-10-2, 3D-11-2, and 3D-12-2) and two 1/10 scale models (CERL No. 1 and 2). When the measured first mode frequency is normalized by the frequency scale factor, N_f, and the peak acceleration is normalized by the acceleration scale factor, N_y, the data can all be plotted on the same curve. (In this notation, the scale factor indicates the ratio of the prototype to the model). In addition, the test conditions had the appropriate added masses and the base motion properly frequency scaled such that the 1/30 scale structure is a 1/3 scale model of the 1/10 scale structure while both structures are models of the assumed prototype. When the data is presented in this manner (Fig. 1), the prototype behavior is shown directly, while the individual model data requires knowledge of the scale factors that were slightly different for the tests. Table 1 gives these scale factors stated as the ratio of the value of prototype to model.

TABLE 1
SCALE FACTORS FOR TEST RESULTS OF FIG. 1

Model	Scale	Scale Factors	
		Frequency N_f	Acceleration N_y
3D-10-2	1/30	1/11.8	1/4.6
3D-11-2	1/30	1/11.8	1/4.6
3D-12-2	1/30	1/12.2	1/5.0
CERL No. 1	1/10	1/6.8	1/4.6
CERL No. 2	1/10	1/7.0	1/5.0

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The lines in this plot (Fig. 1) do not represent "best fit" curves for the data points shown. Rather, they were added to suggest the following conclusions regarding the prototype response as scaled from the microconcrete model response:

1. As shown in Fig. 1, all models suggest that the assumed prototype diesel generator building will have a virgin first-mode frequency of between 7.5 and 8.8 Hz.

2. When subjected to the El Centro N-S earthquake of peak magnitude up to 0.2 g, the prototype will respond with this virgin first mode frequency;

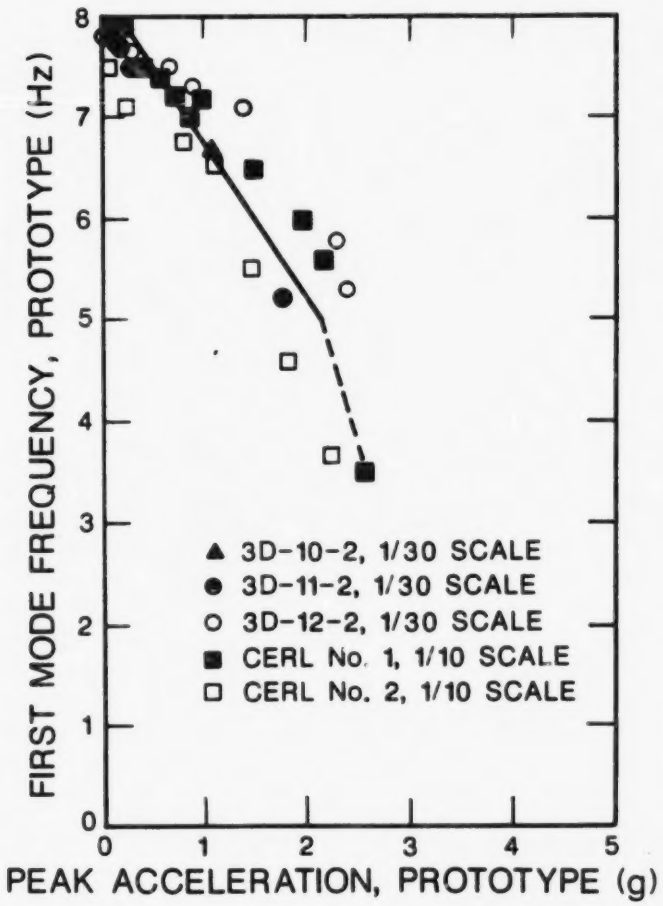

Fig. 1. Prototype Diesel Generator Building 1st Mode Frequencies as Predicted from Scale Models.

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3. If subjected to a peak intensity of greater than 0.2 g's, Fig. 1 shows the prototypes will respond with a reduced effective first-mode frequency. The greater the amplitude, the lower the effective modal frequency. This implies that the floor response spectra for a given acceleration vs time excitation (in this case the El Centro, N-S) will vary with peak amplitude of input which is contrary to the usual linear design assumption;

4. Inspection of the various models indicate that these reductions in modal frequency occur <u>without</u> visible signs of cracking;

5. Low-level, wide-frequency-band diagnostic tests, which were performed between the seismic tests, indicate that any reduction in the effective modal frequency is permanent; and

6. Again, from Fig. 1, the assumed prototype diesel generator building would not completely fail (significant visual cracking and concrete breaking loose from the foundation at the lower walls) until the peak input amplitude exceeded 2.5 g's.

1.2.2 Damping

The quantification of damping associated with the response of structures subject to transient loads which produce nonlinear and/or inelastic responses has proved to be a difficult problem. This is especially true for reinforced concrete structures for which the exact damping mechanism is unknown (that is, is the damping viscous, structural, Coulomb, or perhaps a combination of all three?).

Attempts were made to quantify damping in a way that will be most useful in the analysis process. Therefore, since most analysis methods utilize response spectra and computations which involve equivalent viscous damping ratios, (ζ) here defined in the conventional manner as the ratio of actual damping to the critical damping, these concepts are used in this evaluation. The use of and assignment of values for "equivalent viscous damping ratios (ζ)," does not imply that the damping mechanism is viscous. Rather, it is only an attempt to assign an appropriate value to a term that is needed in response spectra and other methods of analysis.

Two methods of quantifying damping have been used. The first method will be referred to as the "Floor Response Spectra (FRS) Matching Technique" and the second method as the "Transfer Function Analysis Technique (TFAT)."

The "FRS Matching Technique" involves the use of a computer model and iterating with different values of ζ until the computer generated FRS 'match' the FRS generated from response data measured during a test at a given input acceleration level.

The "Transfer Function Analysis Technique" involves plotting the transfer function (TF) of the response acceleration, at a given input acceleration level. The real part of this TF is then examined to determine the damping ratio, ζ. For vibration modes that are not closely spaced, the ζ ratio can

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be calculated from the frequency associated with maximum and minimum values of the function corresponding to a phase value shift at a natural mode.

In Fig. 2 the computed values of ζ from tests of the 1/30 and 1/10 scale models are plotted vs the peak acceleration level. Two levels of peak acceleration are provided: the peak acceleration on the model and peak acceleration in the prototype structure. All of the values, except the two test points indicated as "FRS Matching Technique," were determined using the "Transfer Function Analysis Technique." There is considerable scatter in the data, but the following observations are made.

1. These three types of models respond to inputs with magnitude of less than 4 g (0.8 g on the prototype) as if they have equivalent viscous damping ratios of between 5.5% and 8%.

2. For input magnitudes between 4 and 9 g (0.8 and 1.8 g on the prototype) the effective viscous damping tends to increase.

3. At input magnitudes greater than 9 g (1.8 g on the prototype) (where all of the models are known to be close to failure) the damping is uncertain.

The next important issue concerning damping is whether or not the damping effects are distorted in the models as compared to the prototype, and, if so, how are the effective damping ratios measured in these models related to the effective damping in the prototype. From the scaling law analysis (Ref. 3), one would expect that damping forces are distorted between the 1/30 and 1/10-scale models, only if the damping mechanism is viscous (in this case the equivalent viscous damping ratio of the 1/10-scale model would be a factor of 0.58 smaller than that found in the 1/30-scale models). Analysis of the data plotted in Fig. 2 confirms that the damping mechanism is <u>not</u> viscous (i.e., the factor of 0.58 between the 1/10 scale and 1/30 scale model damping ratio is not seen in the data) and, hence, the values of equivalent damping ratios determined from these model tests are expected to apply to the prototype structure. Also note that, since in both models (1/30 and 1/10-scale) acceleration is scaled by a factor of approximately 5, the region of noticeably increasing damping (region A - B in Fig. 2) corresponds to input amplitude to the prototype in excess of 1 g peak acceleration. This increase in damping does not correspond to the onset of inelastic response as identified in Fig. 1 by a decrease in the structures' resonant frequency.

1.2.3 Floor Response Spectra

How a structure modifies the input base motion is usually expressed in terms of floor response spectra (FRS). The usual design practice is to assume that the structure is a linear system; and, with this assumption, for a given structure subjected to an acceleration signal of a given frequency constant, the FRS is independent of amplitude of the input signal. The structures under consideration have been loaded into their nonlinear/inelastic range. Therefore, it is important to determine how this nonlinear/inelastic response affects the FRS.

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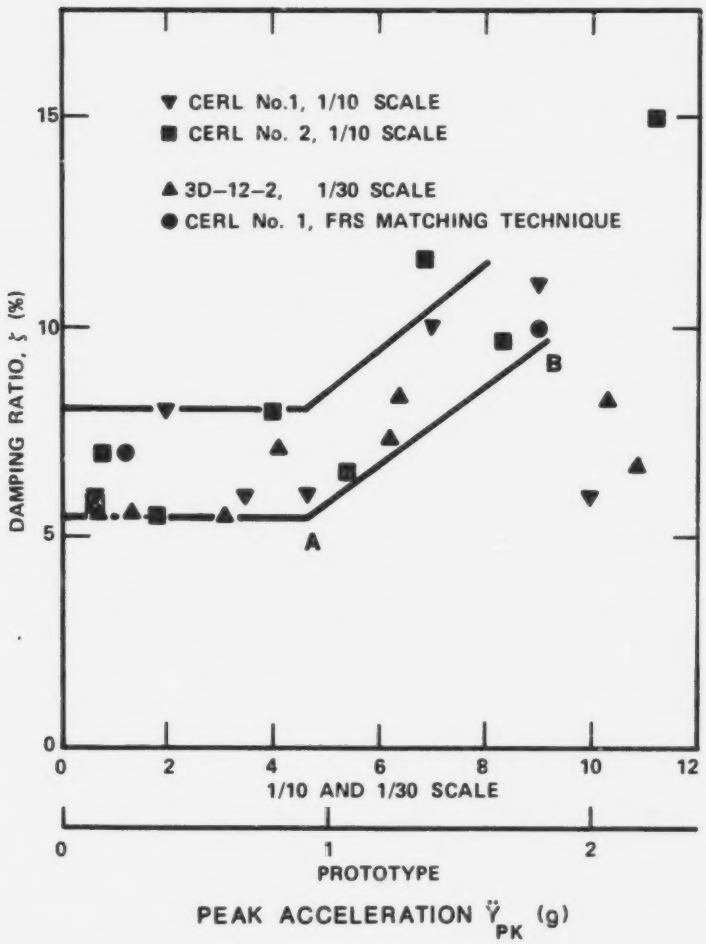

Fig. 2. Damping Measured in 1/30- and 1/10-Scale Models.

This has been done using the data obtained from the tests of a 1/10-scale structure (CERL No. 1). The frequencies and accelerations have been scaled to prototype values. Figure 3 shows the second floor response spectra computed from the measured response at this floor of the 1/10 scale structure during a low g ($\ddot{y}_{pk}/N\ddot{y}$ = 0.26 g) level test. As expected, the maximum amplification occurs in the region of the structure's first mode frequency f_1 = 54 Hz; f_1/N_f = 7.9 Hz. Because this is a stiff structure (relative to the frequency content of the input, the second and higher modes produce relatively insignificant amplifications. Now if this structure remained unaltered at higher input level tests, we would expect that the FRS would remain as shown in Fig. 3. It is known from previous analysis of shifts in modal frequency at higher input levels, that the structure undergoes progressive decrease in stiffness at the higher input levels. Therefore, it is anticipated that the floor response spectra will vary with input level.

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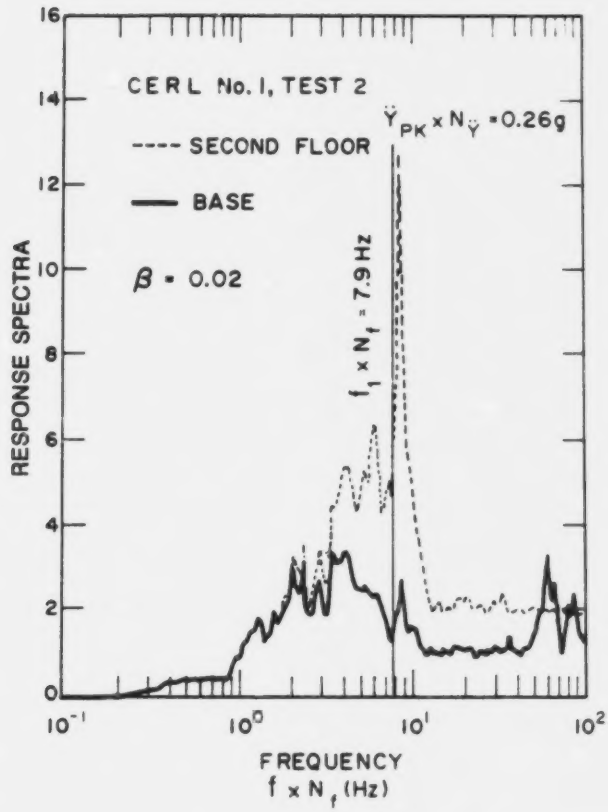

Fig. 3. Response Spectra 1/10-Scale Deisel Generator Building $\ddot{Y}_{pk}$ = 1.26 g.

This is indeed the case, as can be seen by comparing Figs. 4, 5 and 6 to Fig. 3. As the base acceleration input level is increased and the effective first modal frequency is decreased, the frequency region over which amplification occurs is down shifted; and in this particular case, the magnitude of peak amplification is decreased. Note, however, that as the first mode frequency is decreased toward the frequency region in which the input signal is maximum, the amplification of the response in this region is increased; and, if the first mode frequency should be reduced so as to exactly correspond to one of the frequencies at which input level reaches a peak, the maximum amplification of response could, of course, be increased.

1.2.4 Structural Stiffness

The measured stiffness of the isolated shear walls along with measured stiffness values from the static and dynamic tests on the single story 1/30 scale diesel generator buildings are plotted, Fig. 7, versus the models' modulus of elasticity. These stiffness values have been normalized by the corresponding computed stiffness value K_T . The computed stiffness value is one calculated

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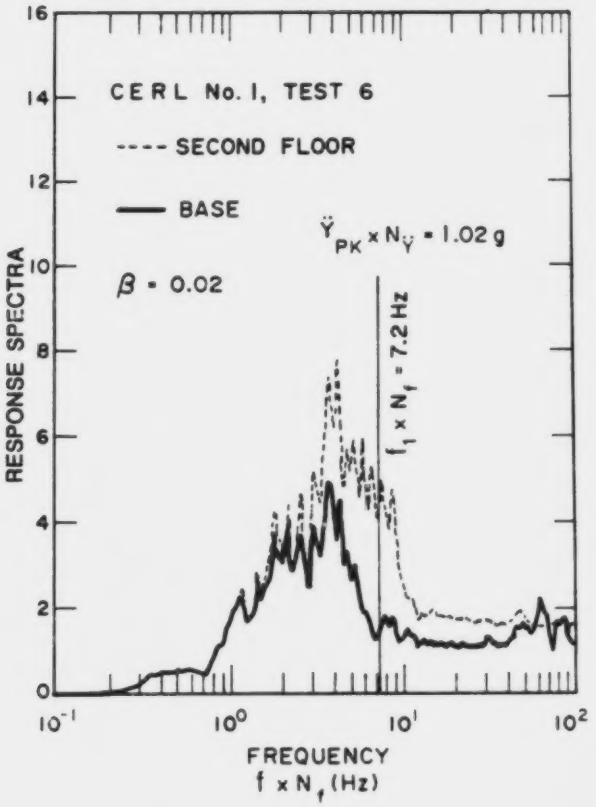

Fig. 4. Response Spectra 1/10-Scale Diesel Generator Building $\ddot{Y}_{pk} = 1.02$ g.

from an uncracked cross section, strength-of-materials analysis. Some variation of the uncracked strength of materials approach is the method A-E firms currently use for determining stiffness of the shear wall. In all cases the working load stiffness (load within the design basis, e.g., less that the SSE) is approximately three to four times less than the calculated stiffness. This reduction in stiffness is independent of the model's geometry and material properties. Although more difficult to quantify, the multi-story models showed similar reductions in stiffness based upon a comparison between the measured fundamental frequencies and the calculated fundamental frequencies. These values are also plotted in Fig. 7.

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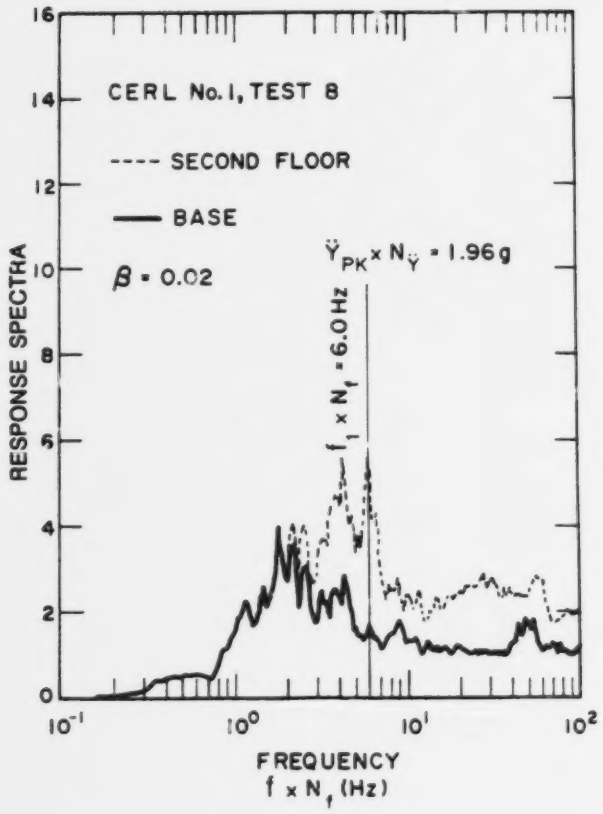

Fig. 5. Response Spectra 1/10-Scale Diesel Generator Building $\ddot{Y}_{pk}$ = 1.96 g.

The reduced stiffness at typical OBE loads in the static tests does not come as a surprise since other investigators' results (Refs. 4, 5, 6) show similar reductions in stiffness, and one of these investigators (Ref. 4) points out that the computed stiffness values only pertain while the structure is uncracked. However, the reduced stiffness during the dynamic tests was surprising in that it occurred at a very low peak g level input (0.5 g peak on the model that corresponds to a 0.1 g peak on the prototype). Analysis of another investigator's dynamic data (Ref. 7) shows similar results and as can be seen in Fig. 1 the structures are responding in an elastic manner at the load levels where the reduced stiffness is first observed.

1.2.5 Summary of Results

At this point in the program the following types of information were available to potential users in NRR. However, credibility needs to be established, especially in the light of analytical/experimental differences that were observed.

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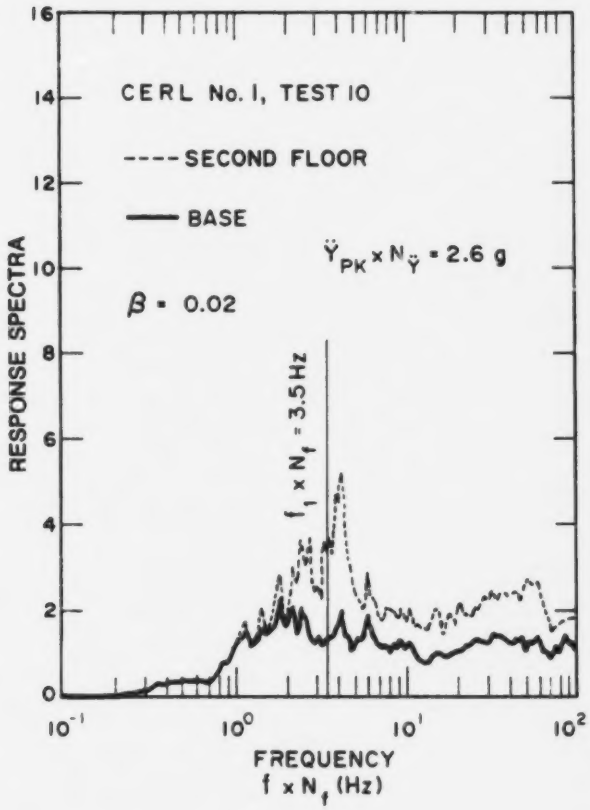

Fig. 6. Response Spectra 1/10-Scale Diesel Generator Building $\ddot{Y}_{pk} = 2.6$ g.

1. Floor response spectra from seismic loads producing elastic and inelastic structural behavior (Fig. 3).

2. Floor response spectra changes as the structures progresses from linear to inelastic behavior (Figs. 3-6).

3. Bounds on earthquake magnitudes at which a structure changes from elastic to inelastic behavior (0.2 g on Fig. 1).

4. The initial stiffness of structures (as related to the stiffness computed using the principles of mechanics) (Fig. 7).

5. The change in stiffness as a structure becomes inelastic.

6. The degradation of stiffness and load carrying capacity as the structure is subjected to a load cycling.

7. The ductility ratio of the structure.

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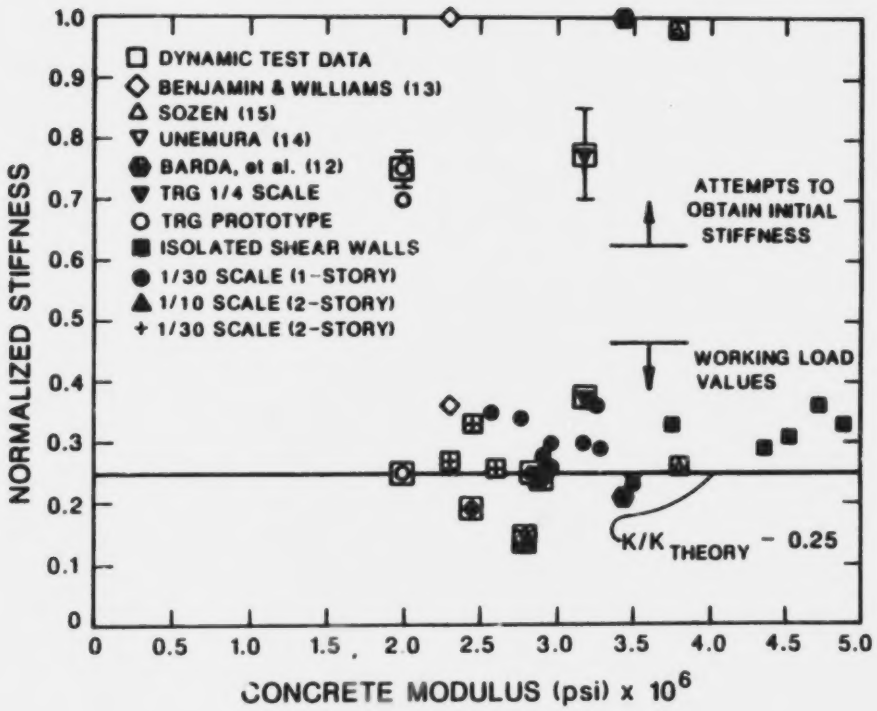

Fig. 7. Summary of Experimentally Determined Stiffness Reductions.

8. The deformation that can be used as a measure of the yield point of the structure.

9. The ductility changes that occur for different configurations of the structure (Ref. 8).

10. The dynamic response and changes in the response for different number of stories, configurations, earthquake loadings, construction details, aging, etc.

11. Changes in equivalent viscous damping as the structure proceeds from elastic to inelastic behavior (Fig. 2).

1.3 Credibility Tests

At the end of FY 1984 the scalability between different size microconcrete low aspect ratio shear wall structures had been demonstrated in both the elastic and inelastic range and the results had been scaled to the prototype structure. Reduced stiffness at low load levels had been observed in all static and dynamic tests and appears to be independent of geometries tested and material properties. This last observation was of particular concern in that current design practices by architecture-engineering firms do not account for this reduced stiffness nor does the current ASCE standard for seismic design of nuclear power plants. The question now arises as to whether the reduced stiffness was caused by the microconcrete and if it would be observed in a

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similar conventional reinforced concrete structure. Also, scaling had only been demonstrated between microconcrete models and again there is some question as to whether results can be scaled to conventional reinforced structures, particularly when the results concern seismic excitation into the structure's inelastic range.

During FY 1985 the Technical Review Group for this program felt that the reduced stiffness observed in these structures was of significant importance and hence must be addressed specifically in the next test structures. In particular, they were concerned as to whether or not a similar reduction in stiffness would occur in a prototype Category I structure made of actual batch plant concrete and conventional reinforcement.

It was recognized that, because all of these tests involved microconcrete models, the observed smaller values of stiffness could be "structural-size" related. Shrinkage cracks that would reduce the effective moment of inertia (I) of the structure, and that would form more rapidly in small sections than in larger sections, must be considered. However, it should be realized that microcracking, caused by shrinkage and nonseismic loads applied during the life of a prototype structure, will exist in prototype structures, and that the reduction in stiffness suggested by these tests may still occur; that is, it may only be a matter of time.

To investigate the effects of microconcrete on the observed reductions in stiffness, three shear wall elements with flexural boundary elements (end walls) were constructed during FY 1985 and FY 1986. The model shown in Fig. 8 was considered the prototype and was constructed with actual batch plant concrete and No. 3 rebar.

The design criteria for this structure are summarized below:

1. maximum predicted bending and shear mode natural frequency $\leq$ 30 Hz;
2. minimum wall thickness = 4 in. (102 mm),
3. height-to-depth ratio of shear wall $\leq$ 1,
4. use actual No. 3 rebar for reinforcing,
5. use standard batch plant concrete,
6. use 0.1 to 1% steel (0.3% each face, each direction ideally),
7. use water blasted construction joints to assure good aggregate and interlock.

These structures will be referred to as the TRG structures after the Technical Review Group that established the design criteria.

The second and third structures were a 1/4 scale model of the structure shown in Fig. 8, but made with microconcrete and wire mesh rebar, as had been

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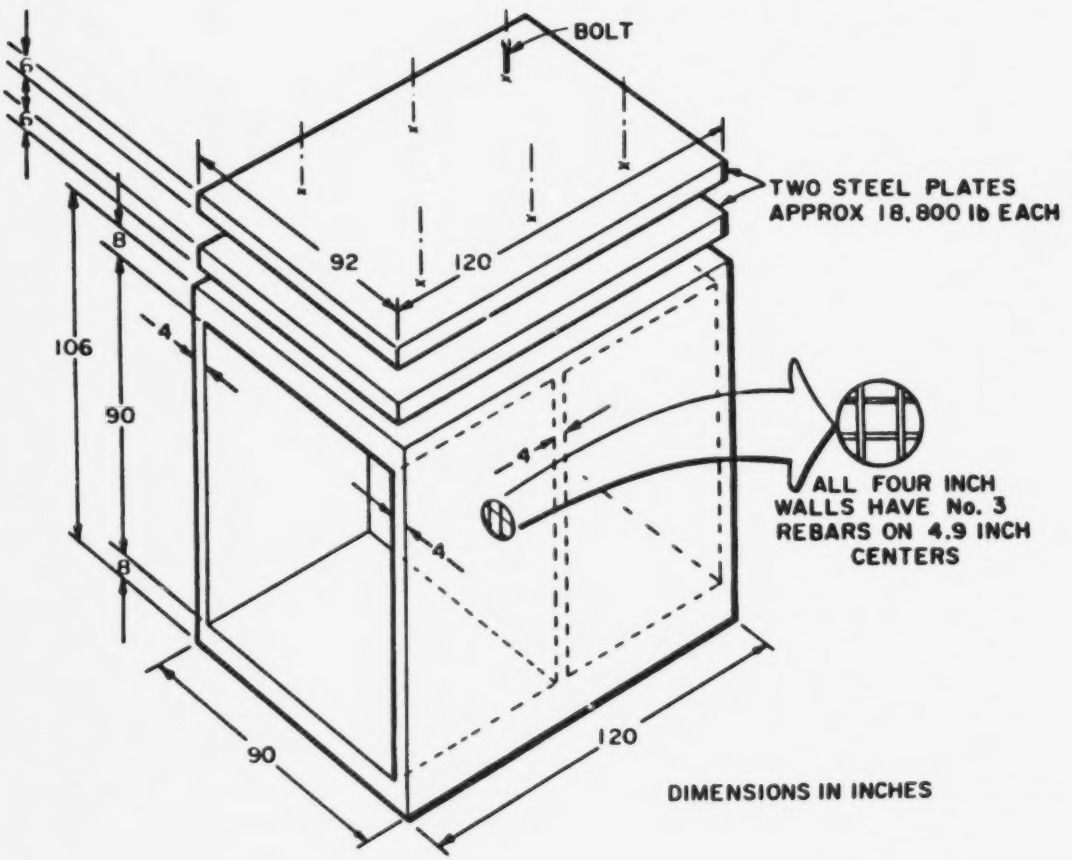

Fig. 8. Prototype TRG Test Structure.

the other microconcrete models. This step was taken in order to quantify any microconcrete effects.

It should be noted that the large added mass was placed on the structure to meet the low frequency requirements. However, this mass also put the normal stresses in the range that an actual Category I structure would experience.

Both the model and the prototype were subjected to low level static testing (max. normal tensile stress less than 80 psi, 0.55 MPa) and low level modal testing (50 lb random excitation) with free-free boundary conditions. A description of these modal testing techniques can be found in (Ref. 9). These tests were used to characterize the initial stiffness and natural frequency of the structure prior to any damage. Next, the prototype and one of the 1/4 scale models were seismically tested to failure or, in the case of the prototype, to testing machine limits in a manner similar to the diesel generator and auxiliary building tests. For the purpose of scaling the seismic input signal (1940-El Centro N-S) the prototype TRG structure was considered a 1/5 scale model of an actual shear wall. The 1/4 scale model was tested at the Los Alamos shake table facility and the prototype was tested at Construction Engineering Research Laboratory. The following results were observed:

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1. During low level static testing, the stiffness of the 1/4 scale models (TRG-1 and -2) and the prototype (TRG-3) were found to be within 70-80% of the calculated stiffness values. Also, the dynamic stiffness based upon results from the low level modal testing techniques fell within this same range. These points are plotted on Fig. 7.

2. Under working loads (loads within the design basis) induced by simulated seismic excitation, both the prototype (TRG-3) and the model (TRG-1) showed similar reductions in stiffness as had been observed in the previous microconcrete model testing. These points are also plotted on Fig. 7. The results from the TRG prototype test represent the first actual seismic testing of a low aspect ratio shear wall element constructed with materials similar to those used in actual nuclear power plant structures.

1.4 Statistically Planned Experiments

Based on the results thru FY 1986, the TRG recommended that further study on reduced stiffness was in order. The TRG felt that quantifying the reduction in stiffness as a function of aspect ratio (wall height to length ratio) and percentage reinforcement steel would be particularly useful for the evaluation of existing plant designs. The TRG stated that the aspect ratios of actual structures range between 0.25 and 1.0 and the reinforcement ranges between 0.125 and 0.5 percent by area, each face, each direction. During the later part of FY 1986, with the aid of a statistician, a set of experiments was developed to examine the range of aspect ratios and percentage reinforcement recommended by the TRG. The configurations used in these tests are similar to the TRG-3 structure except the wall thickness has been increased to 6 inches so that two layers of reinforcement steel can be used. This steel arrangement is more indicative of the actual construction practice for Category I structures.

A matrix defining 9 quasi-static tests identified as points A through C on Fig. 9 was developed. The results from these tests when coupled with existing results would provide an adequate data base for determining stiffness reduction as a function of aspect ratio, percentage of reinforcement steel, wall thickness and load magnitude. The "A" tests were of highest priority; the B's and C's would be done if additional data were needed.

1.5 Analytical Efforts FY 1980 - FY 1986

Although the primary emphasis of this project has been an experimental effort, several analytical studies have been carried out to support the experimental work. These analyses, both elastic and inelastic in nature, have been performed with computer codes called ADINA, ABAQUS, NONSAP-C, and INRES-B. ADINA and ABAQUS are commercial general purpose nonlinear finite element codes. NONSAP-C is a nonlinear finite element code previously developed at Los Alamos to study concrete containments. INRES-B is a code for inelastic analysis of mixed concrete and steel structural systems and uses generalized structural elements such as beams, columns, shear walls, rather than the typical finite element grid.

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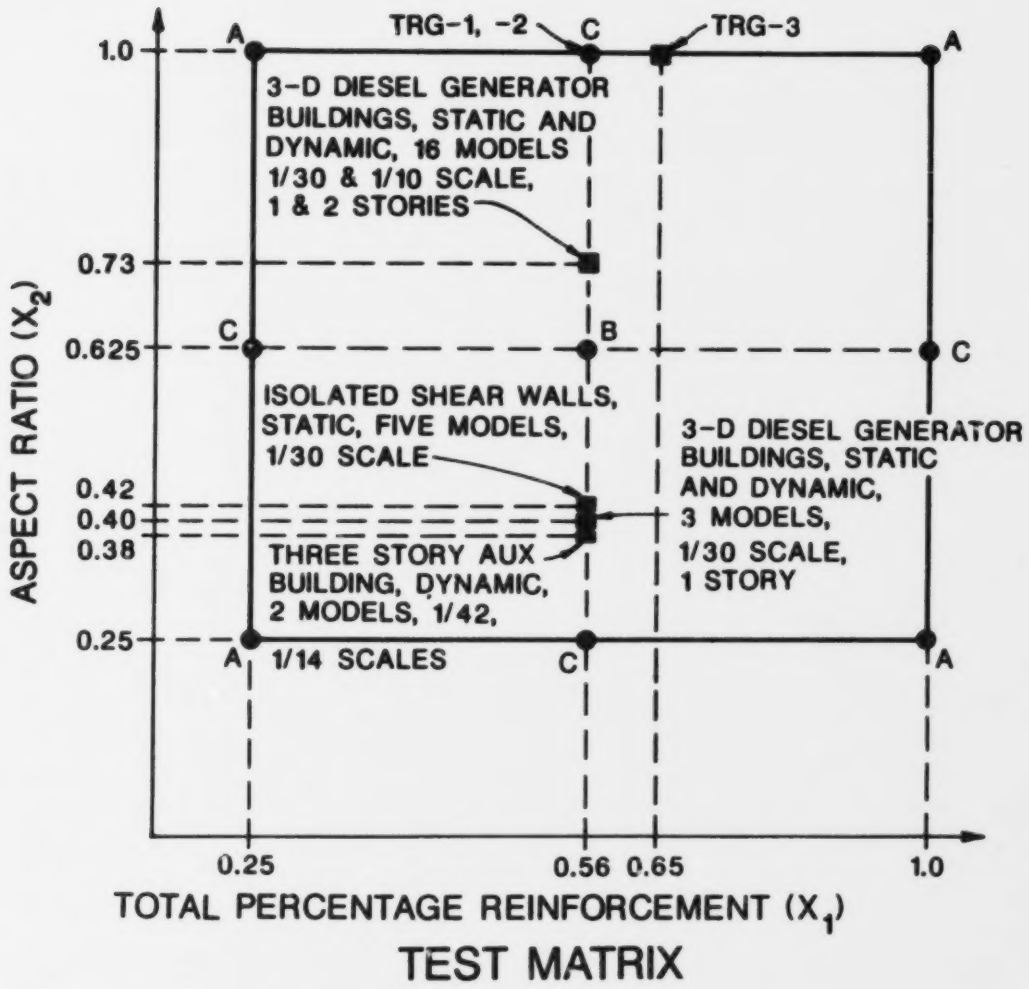

Fig. 9. Statistically Planned Text Matrix.

The ADINA and ABAQUS codes were first used to predict the response of an isolated shear wall. The finite element mesh for one of these models is shown in Fig. 10.

In FY 1983 a frequency analyses of the 1/10 scale diesel generator building was initiated using ADINA. Using a concrete modulus representative of an uncracked concrete wall section, the stiffness of the test structure was computed to be about three times larger than that indicated experimentally from the first mode frequency. However, when using a cracked wall section, the effective stiffness of the structure was in good agreement with the experimental data. Figure 11 illustrates the crack distribution and orientation in the model computed from ADINA--in the end wall tension cracks are formed while

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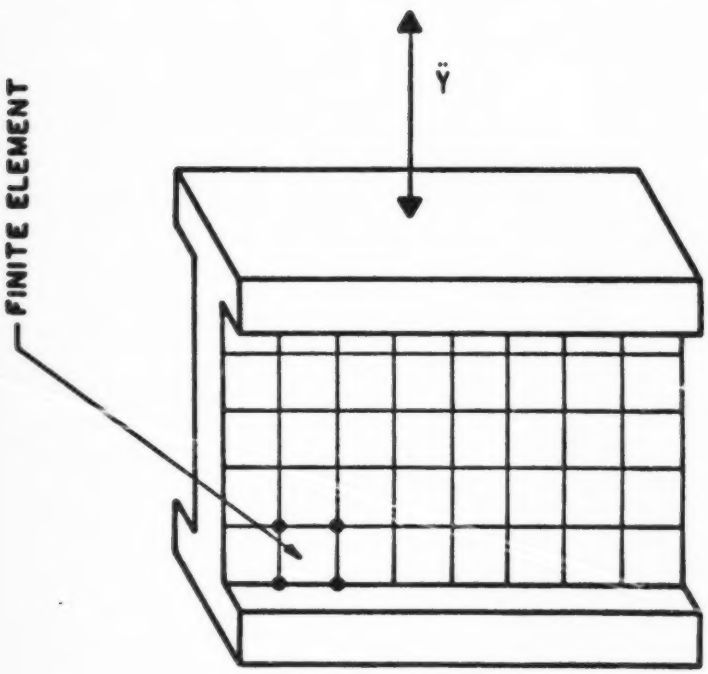

Fig. 10. Finite Element Model of Shear Wall.

in the side walls shear cracks are formed--just as observed experimentally. The difficulty with this type of analysis is in knowing the parameters needed to tune the model to the end result, that is, how should the material properties input to the code reflect cracking in the concrete.

In FY 1983 calculations were also carried out with the INRES-B code in the 1/10 scale diesel generator building subjected to the El Centro accelerogram. The majority of code development has focused on the INRES-B code because it is felt that finite element codes will be impractical for analysis of a shear wall structure due to the large number of elements required to model the structure and the long run times associated with inelastic analysis. In general these calculations were unsatisfactory because the shear wall model correctly modeled post-elastic behavior.

The INRES-B code has been improved to a state in which the calculations carried out in FY 1986 on the 1/10 scale diesel generator building have occasionally demonstrated remarkable agreement with the experimental data. An example of this can be seen in Fig. 12. Other calculations were not as good in predicting floor displacement responses. Further development of this code will be suspended pending FY 1987 tests results.

From FY 1984 to FY 1986 in addition to improving INRES-B the analytical efforts focused on using ABAQUS. ABAQUS was used primarily to determine mode

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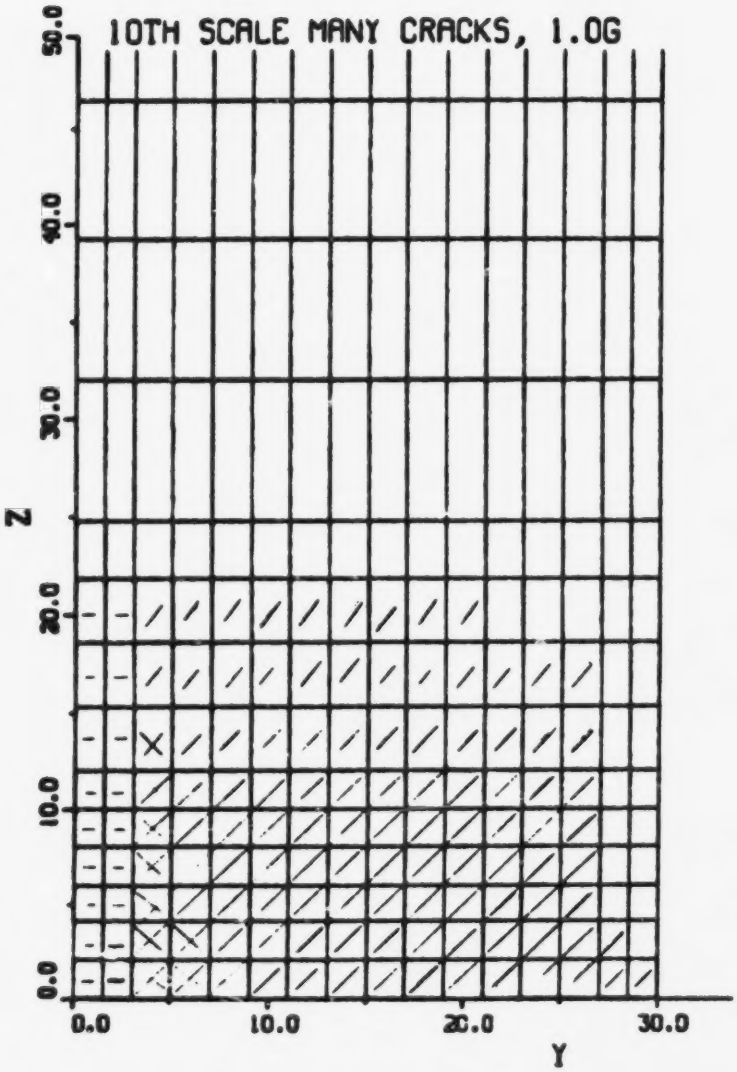

Fig. 11. Finite Element Model Showing Crack Patterns.

shapes and natural frequencies of various test structures as well as investigate shear lag effects (how wide flange or end walls affect normal or bending stress), base fixation effects, and base thickness effects, all elastic calculations. ABAQUS was also used to determine displacement instrumentation for experiments planned in FY 1987. A shear bending mode shape of the TRG-3 structure calculated with ABAQUS is shown in Fig. 13.

Finally, in FY 1986 a commercial experimental modal analysis code was purchased and used on the TRG structures. This type of software has been used extensively in the aerospace and automotive industries, but is relatively new

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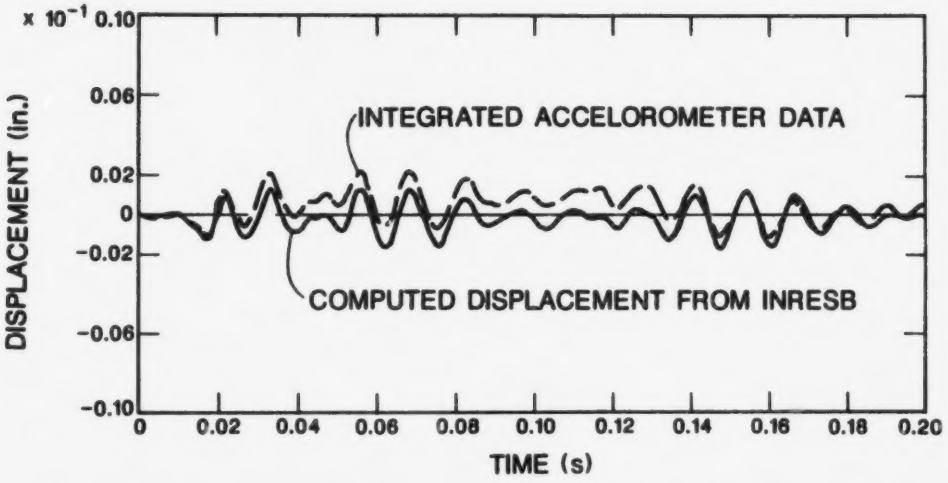

Fig. 12. INRES-B Prediction of 1/10 Scale Diesel Generator Building Response.

in the civil engineering community particularly with regard to reinforced concrete structures. This software interacts with a spectrum analyzer and experimentally acquired frequency response functions to calculate mode shapes, damping and natural frequencies of a structure. Examples of shear-bending mode shapes calculated for the 1/4 scale TRG structure is shown in Fig. 14.

2. Program Plan for FY 1987 - FY 1989

The previous section described program status up through the beginning of FY 1987. The Technical Review Group (TRG) and Los Alamos staff, based on results from the TRG 1-3 experiments (Credibility Test Section), concluded that a significant "microconcrete" influence on the results and preliminary findings is not apparent. That is, analytical/experimental comparisons of structural stiffness could differ by a fac[illegible] of 4. Performing experiments to determine the effects of aspect ratio and percentage of reinforcement steel are important; however, a better balance between testing and analysis is needed. Additional experiments are needed to provide the data base necessary for changing current regulatory requirements. Regulations can not be changed based on the results of the one large scale test performed to date. Analytical emphasis is needed to give an indication of the importance of the analytical/experimental differences (e.g., changes on floor response spectra) and recommend new analytical procedures.

Many variables can contribute to the differences between the analytical/experimental results found so far. A prime candidate is cracking leading to a loss in either bending and/or shear stiffness. Other contributors include end wall effects, poor construction, inadequate base connection, and unknown shake table influence and differences in analytical procedure. Premature cracking could also be a function of handling (shipping, etc) or shrinkage effects, rather than load levels. In any case, a dual analytical/experimental effort is needed to understand the loss of stiffness mechanism and its regulatory impact.

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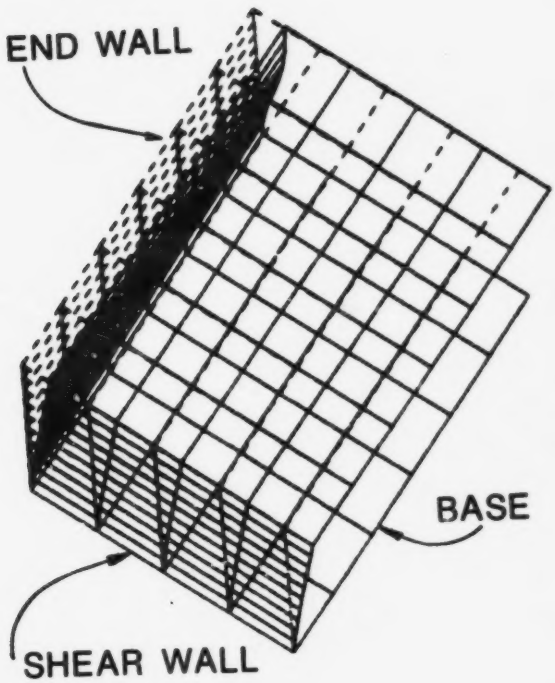

Fig. 13. Shear/Bending Mode Shape Calculated Using the ABAQUS Code for the TRG-3 Structure. The Model has 1/4 Symmetry and the Viewpoint is From the Top Right.

2.1 FY 1987 Program Plan

The TRG and Los Alamos staff agree that the needed experimental information can only be obtained through quasi-static testing on well instrumented structures. Furthermore to minimize handling and shipping related uncertainties, the structures should be constructed and tested in place. An effort to verify the quality of construction (i.e., determine voids in the concrete) should also be undertaken.

To address these issues a better balance of experimental and analytical work has been planned for FY 1987.

2.1.1 Experimental Effort

Three tests will be performed in FY 1987 on a configuration similar to that of Fig. 8. The loading for all these tests will be quasi-static and cyclic (complete load reversal) and is described as follows:

a. 1 cycle that will induce a 50 psi average base shear. This will establish initial stiffness and an "undamaged" hysteresis energy loss. This load level corresponds to the lower cyclic load levels that constitute the majority of a given earthquake signal;

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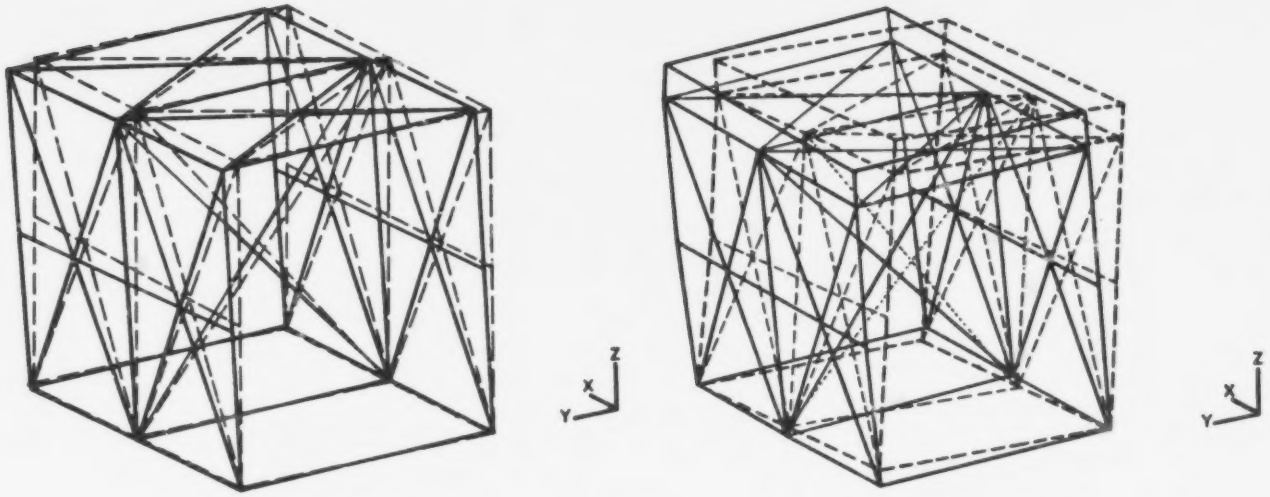

Fig. 14.

(a)
Bare Model Shear-Bending Mode Shape Determined from Modal Testing as a Fixed Base Model.

(b)
Shear-Bending Mode Shape from Modal Testing as a Fixed Base Model With Added Mass. (1/4 Scale Model of a TRG Structure).

b. 3 cycles at 100 psi base shear;

c. 3 cycles at a load level that would increment the average base shear by 100 psi. Repeat until load frame or loading ram capacity, or structural failure indicated by softening (uncontrolled displacement) occurs;

d. 3 cycles at 50 psi average base shear to establish hysteresis losses for the damaged structure.

Many computer programs assume that the hysteresis losses are the same at low load levels both before and after damage. Such an assumption can affect seismic margin calculations. The data from this loading sequence can be used to clarify this assumption and determine structural stiffness degradation.

Table 2 shows the test variables.

TABLE 2
FY 87 TEST SCHEDULE

Test No.	Aspect Ratio	Percentage Reinforcement	Wall Thickness (inches)
1	1.0	0.25	6
2	1.0	0.6	4
3	0.25	0.5	6

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The percentage reinforcing is the total reinforcement each direction. For the 6-inch wall structures, it will be distributed on each face, for the 4-inch wall structure it will be in the center. The 6-inch wall structures address the issues of (a) normal construction practice and (b) differences in aspect ratio. At least the first 6-in. wall model will be ultrasonically tested for voids and cracks prior to testing by a construction and materials consultant to ensure that proper concrete construction practice has been followed.

The 4-inch wall structure is a static repeat of the seismic test performed at CERL (TRG-3). Agreement between stiffness values at corresponding stress levels for static and dynamic tests will clarify the issues of base connection effects and possible unknown shaker table influence. The measurements of stiffness on a quasi-static test are made independent of base connection.

All models will be constructed on the load frame and tested with a minimum of handling to address that issue. The amount of instrumentation will be significantly increased over previous tests to study how the models respond to the applied load. The instrumentation plan has had intensive review by the TRG and NRC staff.

2.1.2 Analytical Effort

The FY 1987 analytical effort will focus on two main tasks. The first relates to calculating structural stiffness. In cooperation with architect-engineering (AE) firms, various modeling assumptions will be employed and the results compared with earlier LANL calculations. This effort will ensure that the analytical practices used by LANL staff are commensurate with those used by industry and not the cause of the analytical/experimental differences of Fig. 7.

The second analytical effort will concentrate on comparing calculated floor response spectra curves with those obtained from test data using the FRS technique. Ideally, linear techniques can be developed to align the peaks (frequency/period and maximum acceleration) of the curves. Adjusting damping will control their magnitude. This procedure will be developed from data on the following model tests:

TRG Model (1- and 4-inch thick walls)

3-story auxiliary building (1-inch thick walls)

2-story diesel generator building (1- and 3-inch thick walls)

Three input accelerations will be used to develop the response spectra curves: low (initial shake table test), medium, and high. The accelerations associated with medium and high will be determined as test data are reviewed so that adequate comparison can be made.

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2.1.3 Code Committee Activities

This program has generated considerable interest among members of national code committees addressing reinforced concrete analysis and design. Presentations of the findings and issues with regard to the reduced stiffness implications on seismic response of equipment and piping were given in November 1986 to both the American Concrete Institute ACI 349 Committee and the American Society of Civil Engineers (ASCE) Dynamic Analysis Committee.

Dr. John Stevenson, a member of the program's technical review group (TRG) is chairman of the ASCE Nuclear Standards Committee. Dr. Joel Bennett, principal investigator for this program, is a member of the ASCE Nuclear Standards Committee. This committee has just approved an ASCE standard for Seismic Analysis of Safety Related Nuclear Structures. The new standard does not include results from this program. Committee members are aware that a portion of the Standard may have to be revised depending upon the outcome of future tests.

Dr. Robert P. Kennedy, also a member of the program's TRG, is chairman of the ASCE Dynamic Analysis Committee. Dr. Kennedy's committee was responsible for developing the Seismic Analysis of Safety Related Nuclear Structures standard. Dr. Kennedy has advised the subcommittee of the Seismic Category I Structures Program results, particularly with regard to the reduced stiffness issue and its implication on floor response spectra. Based on program results, Dr. Kennedy has reconstituted the Working Group on Stiffness of Concrete Shear Wall Structures. The Working Group, chaired by R. Murray, LLNL, will meet bi-annually. Dr. Bennett is a member of the working group.

The Program personnel plan to work diligently with NRC, industry and Code Committees to ensure that best utilization of the research results is forthcoming.

2.2 FY 1988 Program Plan

2.2.1 Experimental Effort

The FY 1988 program plan has three contingencies. If there is reasonable stiffness agreement within the three FY 1987 tests and the previous tests, one course of action will be followed; other, more elaborate courses of action will be taken if the converse is true. Comparison will be made at average base shear stress for corresponding load levels computed from dynamic and static tests.

The first contingency relates to results from the FY 1987 tests agreeing among themselves as a whole, and with previous tests. We will be in a position to close out the program with a few small scale experiments and an analytical effort. The remaining experiments will be to verify that the information we have developed is applicable to a wall with a large penetration, or a building with a missing wall or a building with two different floor configurations.

The first experiment will be on a 1/4 scale TRG type structure with a large penetration in the shear wall. This test will be monotonic static loading. The second experiment will be on a one-story, 1/30 scale diesel generator

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type structure with the end wall missing. This test will be dynamic and in the transverse (short) direction so that torsional response of the model is excited. (Some unreported data on static effects for these open ended 1/30 scale structures has been obtained but not analyzed.) The third experiment involves a two-story, 1/30 scale diesel generator building with an end wall missing on the first floor, the second floor containing all four exterior walls. This test will be dynamic in the transverse (short) direction to study the effects an unsymmetric building has on response. Analytical predictions of the responses of these models due to these geometric effects will be compared to the test results to ensure that we are correctly using the data and conclusions from previous tests.

The second contingency is based on not having agreement within the FY 1987 experimental effort. This will mean that analytical/experimental differences of Fig. 7 are very sensitive to the structures aspect ratio and/or percentage of reinforcing steel. Quasi-static testing of the remaining two "A" points on Fig. 9 (lower left and upper right points) will be performed to extend the data base and aid in developing an analytic method that will give better analytical/experimental agreement. If necessary, the testing of the "B" point on Fig. 9 will be performed.

The third contingency is based on not having agreement with previous tests and the FY 1987 experimental effort. This will mean that analytical/experimental differences of Fig. 7 can be caused by effects or a combination of effects that relate to the test procedures and data reduction. In this case we would plan

1. an intensive review of known good quality tests with regard to testing procedures, obtaining data, and data reduction to improve future test efforts.

2. build two new 1/4 scale TRG models that would be tested as follows:

   a. The first model would be tested only dynamically--first, a modal test for as-built properties; second, a test (without any pretesting and minimum of handling) to a seismic loading equivalent to 0.1 g on a prototype structure. This value is selected because we have previous data on models that indicated reduced stiffness effects at this load level.

   b. The second model would be tested only statically to an equivalent stress level.

Agreement between these tests and the FY 1987 tests implies that prior microconcrete data is flawed by either test procedure, handling history, or data interpretation. In that case, all conclusions about stiffnesses must be based on the FY 1987-88 effort.

After the second or third contingency plans have been completed, the experiments outlined in the first contingency plan for program close-out, will be performed. Tests may be introduced or deleted pending the outcome of foreign cooperative research efforts.

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2.2.2 Analytical Effort

Regardless of the specific contingency followed in 2.1, the enhanced analysis effort in FY 1988 will consist of several parts.

1. A number of miscellaneous analyses associated with the data reduction for quick-look test reports and program planning will continue. In addition, the effort started in FY 1987 comparing calculated floor response spectra curves with those obtained from test data will continue. More input acceleration levels will be investigated.

2. The FY 1987 test data will have information for separating shear and bending effects, rebar strain, and load path and cracking information. A complete nonlinear calculation using the ABAQUS code with the intent to demonstrate that the interaction of these effects is understood will be carried out. This simulation is expected to demonstrate either the robustness or shortcomings of modern analysis methods in some detail. Such a calculation is expensive and would not be the normal practice of an architect engineering firm for the analysis of plant structures.

3. An effort using previous, FY 1987 and/or FY 1988 test data will be started to develop analytical methods to predict structural stiffness as a function of aspect ratio, wall thickness, etc. Such methods would be similar to those that have been used in the INRES-B computer code described previously.

4. The program close out plan will begin. The major effort will be devoted to planning the final reports and digitizing and preparing data in a form that ensures the program objectives are fully addressed. It is clear that in FY 1988 more effort will be required in the areas of data reduction and analytical modeling.

In addition to the above the LANL staff will continue working with the Technical Review Group, NRC staff and other national laboratories to establish a data base useful for seismic probabilistic risk assessments, and seismic design margins and seismic vulnerability assessments. It is also expected that LANL staff will strongly interact with a program that is being established to evaluate the affects of reduced structural stiffness on plant risk.

2.2.3 Code Committee Activities

ASCE and ACI standard committee activities described in Section 2.1.3 (code committee activities for FY 1987) will continue in FY 1988.

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2.3 FY 1989 Program Plan

Closeout activities in FY 1989 will emphasize data reduction and final documentation; no experiments are planned. Preparation of a final report that will include a distillation of all experimental data will be the major effort. In addition, studies will be performed, using the analytical methods developed, assessing the sensitivity of the parameters used in the design of safety related equipment and noncontainment structures to changes in wall configuration, and earthquake magnitude and duration.

Continued interaction regarding program findings with the NRC staff, other affected NRC programs and personnel (domestic and foreign), code committees, and industry is expected.

C. Application of Results

The types of information that will be available to potential users of this research includes:

1. Floor response spectra from seismic loads producing elastic and inelastic structural response, and floor response spectra changes as the response progresses from the elastic to inelastic ranges.

2. Bounds on earthquake magnitudes at which the structural response changes from elastic to inelastic.

3. The initial stiffness of structures (as related to the stiffness computed using the principles of mechanics). The initial stiffness will be investigated as a function of scale of the test structures.

4. The change in stiffness as the structural response becomes inelastic and the degradation of stiffness and load carrying capacity as the structure is subjected to load cycling.

5. The deformation that can be used as a measure of the yield point of the structure and the ductility ratio of the structure.

6. Changes in equivalent viscous damping as the structural response proceeds from the elastic to the inelastic ranges.

The test results from the Seismic Category I Structures Program provide information on the overall or gross behavior of simple buildings and on variations in these buildings. These various structural behavior trends can be reflected in the licensing process by inclusion in Standard Review Plan Sections and Regulatory Guides. By incorporating the behavior trends into design codes, the results can be applied during the design of new plants.

The data from this program can be used to evaluate computer models and programs that are applied to more complex structures. For example, initial tests show that the fundamental frequency decreased to about one-half of its original value before significant cracking occurs. By using the ratio 1/2 and applying it to an existing analysis, the frequency of the actual building just

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prior to major cracking can be estimated. In addition, the analytical methods used to obtain floor level responses and response spectra in the elastic range can be compared to experimentally obtained results. If necessary, new models can be formulated to more accurately predict structural responses. Once acceptable correlation between predicted and experimental elastic response is achieved, inelastic responses can be estimated by comparing inelastic experimental results to predicted inelastic results. By considering increasing earthquake magnitudes, comparing elastic predicted results to experiment trends, and adjusting parameter values, the behavior of a Category I building can be calculated in a rational manner.

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III. EFFECTS OF STRUCTURAL RESPONSE ON PLANT RISK

A. Background

From Fig. 7 (Section II. B.1.2.4, Structural Stiffness) it is concluded that at low load levels the computed structural stiffness value is valid, but at earthquake levels typical of an Operating Basis Earthquake (OBE) or higher the results are consistent and show the structure responding both statically and dynamically with a reduction in stiffness between 3 and 4 or more. This reduction in stiffness has been observed in different scale models of the same structure (1/30 and 1/10 scale diesel generator building models, 1/42 and 1/14 scale auxiliary building models and 1/4 scale and 1 scale TRG structure models). Based on the TRG results, the difference cannot be attributed to microconcrete effects. At this point it is believed that the reduction in stiffness is real and there is no apparent reason why it would not be observed in a prototype Category I structure during an actual operating basis earthquake. If the computed values of stiffness were used to predict the modal frequency of the prototype structure, it would be expected that the values would be too large by a factor of at least $\sqrt{3}$ to $\sqrt{4}$ since modal frequency is proportional to stiffness; this result in turn, would affect all seismic response calculations.

To illustrate the implications of reduced working load stiffness on equipment attached to a low aspect ratio shear wall structure, Fig. 15 compares measured floor response spectra for the top slab of the TRG prototype with computed response spectra for the same location. The measured response spectra was calculated using the measured response of the structure on the top slab. The calculated response spectra used the response determined by subjecting a one-degree-of-freedom lumped mass model to the same base excitation as measured on the TRG prototype. This analytical model was developed using the uncracked cross section computed stiffness for the TRG prototype. From Fig. 15 it can be concluded that existing plant equipment and piping in low aspect ratio shear dominated structures may have been designed to inappropriate floor response spectra. Generalization about the response of equipment in existing designs are difficult to make since the response spectra will be a function of the frequency content of the actual seismic event and the natural frequency of the actual structure. The reduced stiffness will in general lower the frequency of the peak response but can either increase or decrease its magnitude.

B. Research Program Plan

An initial comparison of calculated floor response spectra curves with those obtained from test data (similar to Fig. 15) will be completed in FY 1987 (Reference Section II.B.2.1.2). These comparisons, made on two and three floor building models and a one floor building segment (shear wall and end wall), will provide insights into the magnitude of the analytical/experimental differences for three different earthquake input acceleration levels. Starting in late FY 1987, these data, in combination with simplified piping and systems analytical models, will be used to assess how shifts in structural frequency affect plant risk.

Results and insights from NRC and industry sponsored seismic probabilistic risk assessments (PRAs) and seismic design margins studies will be used to

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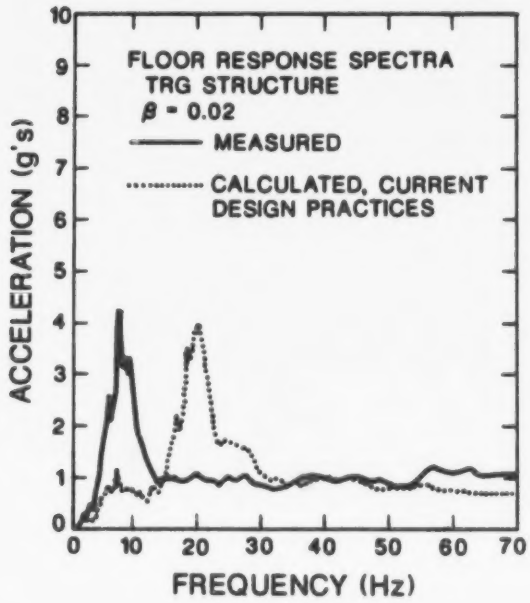

Fig. 15. Comparison of Computed and Measured Floor Response Spectra for TRG-3.

identify the systems and components needing evaluation. In addition, the calculation methods associated with PRAs and seismic margins studies will be evaluated to determine the simplest, most cost-efficient way of determining plant risk.

C. Application of Results

The results from this program will be used to determine the safety significance of the analytical/experimental differences in structural response (e.g., structural stiffness and frequency). If necessary, these results will form the data base for regulatory analyses and cost-benefit analyses that accompany proposed changes to regulatory guides and standard review plan sections.

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16.C

Appendix D
Seismic Component Fragility and Ruggedness Project

NRC Project Manager: John A. O'Brien

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APPENDIX D

SEISMIC COMPONENT FRAGILITY AND RUGGEDNESS PROJECT

1. INTRODUCTION

The fragility of a component is generally defined as the probability of its failure as a function of some forcing or response function. Since components may have several failure mechanisms, there can be a fragility associated with each failure mode. Moreover, some fragilities are recoverable, that is, when the seismic motion ends, component function is recovered. For deterministic seismic margin studies, fragilities are reduced to the use of best-estimate mean values. Seismic fragility is usually expressed as a function of local floor response or is tied to free field peak ground acceleration. One product of this research is a more rational single parameter fragility descriptor based on averaging spectral accelerations over a frequency range. The testing and data collection activities outlined in this program concentrate on seismic fragility; however, fragility can be defined for any type of forcing function, as, for example, hydrodynamic loads. In this research, concurrent pressure, temperature, humidity, and radiation are not included with the seismic shaking.

Current seismic probabilistic risk assessment (PRA) methods for nuclear power plants use component fragilities that are, for the most part, based on a limited data base and engineering judgment. The seismic design of components is based on industry codes and NRC requirements that may not reflect the actual capacity of a component to resist failure. In order to improve the present component fragility data base and establish realistic component seismic design margins, a program was initiated to compile the existing fragility data base and at the same time to independently perform fragility tests on components determined to be important to safety. Besides determining actual seismic design margins and fragilities for selected components, this program will generally enhance understanding of component failure modes and of the various issues affecting fragility.

The specific objectives of the seismic component fragility and ruggedness project are to:

- Systematically identify and categorize electrical and mechanical components important to safety, taking into account system and subsystem functional descriptions, operating and maintenance experience, expert opinion, past PRA results, regulatory concerns, and existing test data.

- Develop procedures for component fragility testing, and demonstrate the effectiveness of these procedures through actual component tests. Obtain useful fragility and seismic margin data for the components tested.

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- o Initiate cooperation with domestic institutions to obtain already existing component fragility data.

- o Assemble, analyze, and interpret existing component fragility data, and compare with information currently being used.

- o Improve seismic PRAs and obtain better estimates of seismic margins by using more realistic test based component fragilities.

- o Develop an improved single parameter fragility descriptor that more precisely reflects failure levels determined from the wide variety of test data (single axis tests versus multiaxis tests, sine sweeps versus sine bursts versus multifrequency inputs).

This program supports the need for reliable inputs for probabilistic risk assessments and margins studies. Moreover, for older operating reactors without any equipment qualification, the staff is now beginning to depend on experience data to allow continued operation. This is a more or less qualitative approach requiring a better foundation, which can only come from an evaluation of controlled laboratory testing such as proposed in this effort.

2. BACKGROUND

There have been no prior efforts directly involving this project. Some fragility data were developed as part of the Seismic Safety Margins Research Program (SSMRP), but this information is based primarily on expert opinion and test data from nonseismic situations. In addition, the nuclear industry, as a result of work sponsored by the Seismic Qualification Utility Group (SQUG), has developed a data base that used past earthquake experience data of nonnuclear facilities in an attempt to demonstrate the seismic adequacy of equipment in operating facilities.

The NRC has completed a cooperative agreement with the Electric Power Research Institute (EPRI) to collect component fragility data. Terms of this agreement were as follows:

1. NRC and EPRI will use a common data format for collection of information from various sources. It is understood that owing to the specific nature of the individual program, NRC and EPRI may gather additional information about a test to meet their own specific needs for compilation of the data.

2. NRC and EPRI will coordinate their data acquisition effort, e.g., visiting a source organization, collecting a test report, etc., in order to avoid duplication as far as possible. It is agreed that EPRI will primarily collect data from the utilities and west coast testing laboratories, and NRC will primarily approach vendors and east coast testing laboratories.

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3. NRC and EPRI will exchange data sheets and pertinent information. It is recognized that, in many instances, information in the form of a data sheet may not be adequate for either program; a review of the test report may be required.

The seismic component fragility and ruggedness project is being conducted in two phases. Phase I (FY 1985) activities consisted of parallel efforts to (1) develop and demonstrate procedures for performing component tests to obtain new fragility data, (2) identify, through systematic grouping, components important to safety and therefore candidates for extensive data evaluation, and (3) acquire and evaluate existing component fragility data from all sources.

Phase II (FY 1986 through FY 1988) of this project is being devoted to the evaluation of the extensive data base. Sources of data include Westinghouse, General Electric, Brown Boveri, Telemecanique, United Controls, and ANCO Engineers.

The plan of approach as well as the objectives and scope have been approved by NRR and by the ACRS Subcommittee on Extreme External Phenomena. We are coordinating our work with major efforts ongoing in RES.

3. PROGRAM PLAN

In the purest statistical sense, empirically developing a meaningful seismic fragility for a given component would require that a large population of identical components (e.g., several hundred or several thousand) be subjected to successively higher levels of acceleration. Within practical constraints on time and resources, this is hardly feasible for a single component under well-defined load conditions, let alone for the effectively infinite combinations and permutations of component type, mounting, loading conditions, etc., that could be identified for actual nuclear power plants. However, a substantial amount of seismic fragility information is available from pre-existing tests and this information is being made available to NRC contractors.

The approach adopted in this program takes advantage of the fact that, for PRA application, a limited fragility description may be adequate. This is because in a probabilistic analysis, failure occurs only when the probability distributions of response and fragility overlap. In those cases where only the tails of these distributions overlap (as would be the case, for example, for a component with a high safety margin), only the lower portion of the fragility curve would be of interest from a PRA standpoint. Therefore, the amount of information on such a component could be limited substantially and still provide adequate information.

For a component having a high margin against seismic failure, the degree of overlap of the response and fragility distributions could conceivably be so small as to imply that the probability of a seismic failure is effectively zero. In such a case, it would have little meaning to empirically describe fragility for PRA purposes.

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Phase I of the work was completed at Brookhaven National Laboratory (BNL) and Lawrence Livermore National Laboratory (LLNL).

For Phase I of the project, the scope of work was as follows:

The BNL portion of the Phase I effort involved five tasks:

1. Establish lines of communication with vendors, owners, and testing laboratories to determine availability of already existing component fragility data;

2. Negotiate, to the extent possible, the transfer of existing component fragility data to BNL;

3. Host an international workshop on component fragility to identify sources of information and issues and concerns.

4. Use all sources of information to assemble, analyze, and interpret available fragility data for selected components. The selected components took into account the component prioritization undertaken by LLNL and the recommendations of the consultants retained by LLNL. In turn, the LLNL component prioritization was based in part on the information obtained by BNL.

5. Compare results with component fragilities used in current PRA and seismic margin studies and recommend improvements where possible.

The LLNL portion of the Phase I effort involved five tasks:

1. Develop component group and prioritization.

2. Develop Phase I test procedures.

3. Perform Phase I tests.

4. Review and document test results.

5. Develop Phase II program plan.

In order to reduce to a manageable level the number of components included in a comprehensive data collection program, it was necessary to prioritize components important to safety. Past efforts to develop generic equipment lists through the use of PRA models, such as by LLNL during the SSMRP as well as by BNL, have met with limited success. The results of these efforts suggested that the apparent importance of components was strongly influenced by event trees and fault trees, which are characteristic of a specific plant, and by the fragility data used in the PRA study, which was based primarily on expert judgment.

In view of these limitations, an alternative approach to systematically identify, categorize, and prioritize electrical and mechanical components

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important to safety was taken. This approach took into account plant system and subsystem functional descriptions, expert judgment, past PRA results, regulatory concerns, existing test data, and plant operating and maintenance experience. Components were grouped by function. Subgroups were established according to the technical issues affecting the fragility of a given component.

The actual component grouping and prioritization was performed by LLNL and its consultants and led to the following prioritization list.

GROUP A (VERY IMPORTANT ELECTRICAL EQUIPMENT WITH LOW SEISMIC CAPACITY)

1. Switchgear
2. Electrical Racks and Panels
3. Instrument and Control Panels and Racks
4. Auxiliary Relay Panels
5. Local Instruments
6. Motor Control Centers
7. Relays
8. Circuit Breakers

GROUP B (VERY IMPORTANT ELECTRICAL AND MECHANICAL COMPONENTS WITH MEDIUM SEISMIC CAPACITY)

9. Horizontal Motors
10. Diesel Generators
11. Batteries and Battery Racks
12. Transformers
13. Air Handling Units
14. Power Supplies
15. Communication Equipment
16. Inverters
17. Bistables
18. Fire Protection and Deluge Equipment
19. Control Rod Drive Equipment
20. Bearing Cooling Equipment

Parallel to the grouping and prioritization of power plant components, LLNL and its consultants developed fragility test procedures that were applied in Phase I demonstration tests on selected components. The actual tests were performed by Wyle Laboratories (Norco, California) under subcontract to LLNL. LLNL and Wyle jointly developed the Phase I test procedures. The components to be tested were selected by LLNL and Wyle, based on judgment of their importance and the component characteristics that can be used to demonstrate the overall testing philosophy and procedure. This made it possible to begin actual testing early in Phase I before component prioritization was completed.

The demonstration tests were performed on two types of motor control centers, one with a stiff frame and one with a flexible frame. Anchorage of the motor control centers was one of the variables in the testing.

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As a result of data evaluations undertaken during Phase II of the project, the following tasks will be performed:

1. Analyze the test results and compare with fragilities used in current PRAs and seismic margin studies. Focus on electrical components with low seismic resistance. Develop an improved single parameter fragility descriptor.

2. Identify all significant failure modes, including partial and intermittent component failures. Determine which failure modes are recoverable (operation after seismic motion returns).

3. Define the limitations of the present fragility data base for the tested components, and recommend improved fragility curves. Indicate how input frequencies affect the fragility of relays.

As a part of this task, the contractor will also develop methods to extend the results to all the components within each group.

4. APPLICATION OF RESULTS

These efforts have led to the establishment of a Component Fragility Data Bank at Brookhaven National Laboratory. No standard review plan sections or regulatory guides will be influenced by this work.

Results from the seismic component fragility and ruggedness project will primarily be used in seismic PRAs and margin studies. It is expected that more realistic component fragilities will lead to simplification of the seismic PRA methodology through the elimination of insignificant branches on event trees and fault trees. Additionally, uncertainties in the present data base, which in turn cause uncertainties in risk estimates, should be reduced as a consequence of these endeavors.

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Appendix E
Validation of Seismic Calculational Methods Program

NRC Project Manager: James F. Costello

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APPENDIX E

VALIDATION OF SEISMIC CALCULATIONAL METHODS PROGRAM

1. INTRODUCTION

There is a high-priority need for reliable assessment of the possible consequences to the public if a nuclear power plant were subjected to an earthquake significantly larger than considered in its design basis. That need is documented in the following correspondence:

- Memorandum from J. J. Ray (ACRS Chairman) to N. J. Palladino (Commission Chairman), dated 1/11/83, on "Quantification of Seismic Design Margins."

- Memorandum from J. C. Ebersole (ACRS Chairman) to N. J. Palladino (Commission Chairman), dated 1/18/84, on "Quantification of Seismic Design Margins."

- Memorandum from W. J. Dircks (EDO) to J. C. Ebersole, dated 4/12/84, on "Quantification of Seismic Design Margins."

- Memorandum from W. J. Dircks (EDO) to Chairman Palladino, dated 4/12/84, on "Quantification of Seismic Design Margins."

Seismic probabilistic risk assessment (PRA) methods have been applied to identify safety issues for nuclear power plants. A common outcome from these assessments is the perception that seismic events can affect many plant systems simultaneously and, therefore, can be a significant or even dominant contributor to overall risk. The randomness of the seismic hazard, the uncertainties and variabilities of the needed data, and the approximate nature of the methodology used raise questions of credibility with respect to the results of seismic PRAs. This, in turn, leads to questions about the conclusions drawn regarding safety implications and regulatory actions. Some possible uses, such as comparisons of alternative courses of action, may be less sensitive to residual uncertainties than others, such as quantitative estimates of public consequences. But, while the accuracy needed depends on the intended end use of seismic PRAs, it is nevertheless necessary to validate the methodologies so they may be used with confidence and credibility in the regulatory decision process.

The objective of validation research is to obtain information that can be used by NRC to improve predictions of the behavior of nuclear power plants subjected to large earthquakes and thus improve the regulatory process. The predictive methods to be validated are used in both probabilistic and deterministic calculations.

The fundamental strategy is to engage in cooperative research programs in order to best stretch available resources. Three efforts have been developed:

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1. Participation in a soil-structure-interaction experiment being performed near Lotung, Taiwan, by the Electric Power Research Institute (EPRI).

2. Participation in the Phase II experiments being performed at the Heissdampfreaktor (HDR) facility in Kahl, Federal Republic of Germany (FRG), by Kernforschungszentrum Karlsruhe (KfK).

3. Participation in tests of a 1/2.5-scale model of a PWR piping loop to be performed on the large shaker table in Tadotsu, Japan, by the Nuclear Power Engineering Test Center (NUPEC).

The scopes of these efforts are outlined in Section 3.

2. BACKGROUND

There have been attempts, mostly since the 1950s, to assess the adequacy of mathematical models of the behavior of large civil engineering structures during earthquake ground motions. For the most part, excitation levels have been low, and the responses measured may well not reflect behavior during very strong ground shaking. However, a necessary step toward understanding behavior in the nonlinear range is an understanding of how well linear models do in the range where they should work well.

For most civil engineering structures in seismic regions, the largest dynamic design load comes from postulated earthquakes. Most of the dynamic tests were performed mainly for verifying the design model. But since, in most tests, the excitation levels were very low compared to seismic excitation levels, the design model could not be said to be truly verified for earthquake loading. If a structure, which was dynamically tested, also was instrumented and monitored during natural earthquakes, a good means of evaluating the test results is available. Only a few structures were subjected to both dynamic tests and earthquakes, with the response to the latter serving the same purpose as the test records.

Tanaka et al. (Ref. 1) compared the period and damping values of fundamental translational modes of 17 multistory buildings in Tokyo obtained from pre-earthquake ambient testing with those determined from response to a 1968 earthquake of magnitude 6.1. The maximum response amplitudes of buildings ranged from 3 to 25 microns (1 micron = 10^{-6} m) in the ambient tests and from 0.3 to 8 cm during the earthquake. Thus, the earthquake-response amplitudes were about three orders of magnitude higher than the ambient-response amplitudes. The structural periods during the earthquakes increased on the average by about 20% compared to the corresponding values obtained from ambient tests. However, as the authors note, no such simple trend is observed for damping ratios. Though there is a tendency for the damping to increase with amplitude for most buildings, an opposite tendency was observed in a few others. Since the method of determination of damping values from ambient or earthquake records is not considered very reliable, the value of the comparison

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of damping values is somewhat limited, as the authors themselves point out. Udwadia and Trifunac (Ref. 2) compared ambient, forced, and earthquake-excited vibrations of the Millikan Library (nine-story steel frame building). In the Millikan Library building, the forced-vibration tests and three sets of ambient tests were pre-earthquake tests. These tests were followed by the Lytle Creek earthquake of 1970 and the San Fernando earthquake of 1971. Post-earthquake vibration tests included ambient tests soon after the 1971 earthquake and vibration tests many months later in 1972. It was noted that dynamic parameters showed marked variations during the earthquakes.

As noted by McVerry et al. (Ref. 3), the level of excitation in the San Fernando earthquake was 10 times that of the Lytle Creek earthquake. The Lytle Creek response was six orders of magnitude greater than typical ambient-test response. Yet for the low level of excitation in the Lytle Creek earthquake, it is noted (Refs. 3 and 4) that the identified natural periods were close to those measured in pre-earthquake tests. On the other hand, for the San Fernando earthquake, a marked reduction from the pre-earthquake test values of apparent natural frequency is noted. According to figures given by Udwadia and Trifunac (Ref. 2), the reductions are about 20% in the N-S fundamental frequency and about 33% in the E-W fundamental frequency. McVerry and co-workers (Refs. 3 and 4) also state, on the basis of their analysis of the San Fernando earthquake records, that the N-S and E-W fundamental periods increased from vibration-test values of 0.52 and 0.69 seconds to 0.62 and 1.00 seconds, respectively, during the strongest portion of the earthquake. The ambient tests that followed the San Fernando earthquake showed that, compared to the pre-earthquake values, the natural frequencies still showed a reduction ranging from 4.8 to 14%. However, the vibration tests of 1972 showed that the natural frequencies continued to recover (i.e., increase) and approached almost their pre-earthquake values (Ref. 2).

In the JPL Building 180, the forced-vibration tests of 1963, three earthquakes during 1968-1971, and the post-earthquake ambient tests of 1971 form the basis of comparisons. Here again, for the purpose of these comparisons the entire record of each earthquake was used by the authors to compute transfer functions. The authors demonstrate through these transfer functions that the apparent E-W and N-S translational natural frequencies during the San Fernando earthquake decrease from the values of the forced-vibration tests by about 15% and 20%, respectively. The other two earthquakes of 1968 and 1970 generated response amplitudes of only about one-tenth of the San Fernando earthquake, and during these earthquakes the apparent natural frequencies decreased somewhat, but recovered to the pre-earthquake, test-determined values. The ambient tests (performed about 6 months after the San Fernando earthquake) showed that the natural frequencies recovered (i.e., increased from earthquake values) to within 6% of the forced-vibration test values.

Udwadia and Trifunac (Ref. 2) performed a moving-window Fourier analysis of the 1970 and 1971 earthquake records to study the variation of natural frequencies during the different phases of an earthquake. Based on a

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comparison of different natural frequency values (of a given mode) during an earthquake with those obtained from pre-earthquake tests, the authors state that the fundamental frequency during moderate earthquake excitations may decrease by as much as 50% of the values determined by pre-earthquake dynamic tests. This decrease (in the two cases reported) was not accompanied by any observable damage, and in both cases the post-earthquake tests showed that the fundamental frequency recovered with time and approached pre-earthquake test values without any repairs. While being unable to ascribe the nonlinear behavior shown by the comparisons to any particular cause, the authors speculate that nonstructural damage might be responsible for such behavior and that the apparent frequency changes may be characterized by time-dependent nonlinear hysteretic behavior. Foutch and Housner (Ref. 5) have considered the various possible contributing factors to the nonlinear behavior of this building.

The changes observed in the fundamental frequencies of the Millikan Library building during the course of many dynamic tests and the San Fernando earthquake also gave rise to many studies (Refs. 6 through 9). In one of these studies, Luco et al. (Ref. 6) give tables showing the values of fundamental frequencies determined from different dynamic tests (both before and after the earthquakes) and the Lytle Creek and San Fernando earthquake records. The values of apparent modal damping of the first E-W mode from some of these tests and earthquakes are also given. The frequency values generally confirm the trends noted by Udwadia and Trifunac (Ref. 2) and McVerry et al. (Refs. 3 and 4). The apparent damping ratios during the San Fernando earthquake are noted to have increased to about 5.5% from the pre-earthquake test values of about 1.5% and subsequently to have decreased to post-earthquake test values of 1.3-1.8%.

An 11-story steel frame building in Japan was subjected to forced-vibration tests subsequent to which it was subjected to many earthquakes. Murakami et al. (Ref. 10) have reported on the analysis of the test response to two of the earthquakes. Since the test amplitudes are given in terms of displacement and the earthquake amplitudes are given in terms of acceleration, the levels of excitation of the test cannot be compared with those of the earthquake. The authors note that the natural periods determined from earthquake response are longer than those obtained from forced-vibration tests. For example, the fundamental N-S period increased from 0.48 to 0.52-0.56 s and the E-W period from 0.31 to 0.38-0.42 s. Thus it is seen that the increase in period ranges from 8-30%. The authors do not seem to have investigated the variation of damping characteristics. One other point noted by the authors is that the higher-mode vibrations of the slabs observed in the dynamic tests were suppressed in the largest-amplitude earthquake vibrations. This is interesting because, if the earthquake records had been used as input for parameter estimation, the slab modes would not have been identified. A nine-story reinforced-concrete frame shear-wall building in Japan was subjected to forced-vibration tests in 1969, 1970, and 1971. Earthquake response of this building was observed from 1969 onward, and Shiga et al. (Ref. 11) reported that,

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during 1969-1970, 17 earthquakes were recorded. The authors have selected three 1970 earthquakes for comparison with the three sets of forced-vibration tests. In this case, too, it is not possible to compare the levels of excitation of the tests on the one hand with those of the earthquakes on the other because of insufficient data. The fundamental natural periods for the earthquakes are seen to have increased by various percentages from test values. The vibration-test results in themselves seem to indicate that the natural periods tend to increase with time. But this may be misleading, as the intervening earthquakes may have been at least partially if not fully responsible for this apparent period lengthening.

Ohta et al. (Ref. 12) compared the natural periods of 11 tall buildings in Japan obtained from forced-vibration tests with those obtained from the earthquake response records. This comparison is somewhat questionable because the vibration tests were performed before the buildings were completed while the earthquake responses were measured after the buildings were completed. The authors note that the acceleration amplitudes of 21 earthquakes that occurred from 1968 to 1979 ranged from 10 to 50 times larger than the acceleration amplitudes of the vibration tests. According to the authors, the fundamental periods determined from earthquake response were on the average 30% longer than those determined from vibration tests.

Ogawa and Abe (Ref. 13) report on their investigation of stiffness degradation of 205 buildings due to earthquakes by performing ambient tests before and after two strong-motion earthquakes. Strictly speaking, this work is not a comparison of test and earthquake behavior. Yet, since the post-earthquake tests were performed immediately after the earthquake, possible recovery would have been small, and it is not unreasonable to assume that the post-earthquake tests reflect the same dynamic characteristics of the buildings that the final, low-excitation portion of the earthquake records would have indicated. The buildings, located in the Sendai area of Japan, ranged in height from 1 to 18 stories and included various types of construction. The maximum recorded ground accelerations during the two 1978 earthquakes were in the range of 0.25-0.4 g. The buildings under investigation showed various extents of damage, ranging from almost no damage to severe shear failure in columns. The authors also relate the degree of damage to the change in natural period. They state that the average value of the ratio of the natural period measured after the earthquakes to that measured before is 1.31 and that there is a strong correlation between the extent of damage and this ratio.

Test- and earthquake-determined characteristics were compared for the 42-story steel frame Union Bank building in Los Angeles (Refs. 3 and 14). Ambient tests were performed on this building both before and after the 1971 San Fernando earthquake (Ref. 15). The San Fernando earthquake response was analyzed by Beck and Jennings (Ref. 14) to determine the modal parameters of the building. Comparing the pre-earthquake ambient-test values and the values determined from earthquake response, it is seen from Reference 14 that all the four natural periods determined increased by about 50% during the earthquake. The fundamental-mode damping ratio also showed an increase from the pre-earthquake ambient-test values of 1.7% to a value of 4.2% during the

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earthquake. The higher-mode damping ratios showed an even larger increase. The effective participation factors determined from ambient-test response were also found to be different from those determined from the earthquake response. The effective participation factors represent the mode shapes in a sense. Beck and Jennings (Ref. 14) note that this last mentioned result was somewhat unexpected. They conjecture that the fundamental-mode mode shape during the earthquake might have been different from that during the ambient test.

A comparison of natural periods determined from the earthquake response with those obtained from the post-earthquake ambient tests shows that all the values decrease and tend toward their pre-earthquake test values. The recovery was not complete. The fundamental period, which increased from a pre-earthquake value of 3.1 s to an earthquake value of 4.61 s, decreased to only 3.8 s at the time of the post-earthquake ambient test. Since no further series of post-earthquake tests is reported to have been performed, it is not known if the recovery continued with time.

The final example of a building subjected to both testing and earthquake excitation concerns the Bank of California building in Los Angeles (Ref. 3). This 12-story reinforced concrete building suffered substantial structural damage during the San Fernando earthquake. Ambient tests were performed after the earthquake. McVerry et al. (Ref. 3) note that this building showed a great period lengthening during the earthquake. They state that the fundamental period identified from a late segment of the earthquake response record was 2.37 s, whereas the post-earthquake ambient tests indicated a value of only 1.62 s.

Another large civil engineering structure subjected to both vibration tests and earthquakes was the Santa Felicia earth dam. The response of this modern rolled-fill embankment to two earthquakes (of magnitudes 6.3 and 4.7) was analyzed by Abdel-Ghaffar and Scott (Ref. 16). After the two earthquakes, ambient and forced-vibration tests were performed on the dam (Refs. 17 and 18). Abdel-Ghaffar and Scott also made a comparative study of the response of the dam to the earthquakes with the response to the tests (Ref. 19). The following observations are summarized from that study.

The maximum accelerations at the crest were 0.2 g and 0.05 g for the earthquakes and 0.000037 g in the forced-vibration tests. The period of the first upstream-downstream shear mode was longer during the earthquake by 13% compared to the forced-vibration tests. The authors note that, though the water level in the reservoir was not the same during the earthquakes and the tests, the differences in levels were not large enough to affect the period values significantly. During the earthquakes, the response was primarily in the first mode, and very few higher modes were excited in the upstream-downstream direction. In contrast, in all the dynamic tests many higher modes were clearly excited. The authors also discuss the difference between the earthquakes and the different tests in exciting various other modes. The damping ratios are given to have increased from a range of 3-4% for the tests to a range of 5-15% for the stronger of the two earthquakes.

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The previous example completes the review of comparisons of dynamic test and earthquake response of structures. A different but closely related comparison will be briefly reviewed. Blume (Refs. 20 and 21) compares the dynamic behavior of buildings subjected to vibrations from underground nuclear explosions (UNE) with that observed during natural earthquakes. Many high-rise buildings in Las Vegas, Nevada, were monitored to measure their response to many UNEs. The response of the same buildings to natural earthquakes was also measured with the same instruments. The strongest of these earthquakes is the San Fernando earthquake of 1971. Unlike the comparisons reviewed until now, some of the UNE events produced response amplitudes greater than those from the San Fernando earthquake. The response amplitudes were of the order of a few hundredths of a "g." Comparing the variation of the period at which the maximum response is noted to occur in the UNE and the earthquakes for six typical high-rise buildings, Blume notes that the periods are not constant and that they vary with both amplitude and time. He notes that though some correlation has been obtained between period and amplitude and between period and time, some of the variations must be considered random. Noting that natural periods of complex buildings are not constant, and that the natural separation of random bonding between nonstructural elements has resulted in noticeable period changes, he remarks that period changes do not necessarily indicate damage. He states that, in general, period and damping tend to increase with time, with loading, with amplitude, and with prior history of loading. He points out that fundamental-period increases of up to 40% and damping increases of up to 100% have been found in the Las Vegas buildings in the course of the many UNEs and earthquakes.

Finally, in the context of this section, reference to a paper by Yao and Schiff (Ref. 22) is appropriate. In this paper, the authors have considered the application of system identification techniques to three situations: the analysis of test data, the analysis of strong-motion response data, and the analysis of post-earthquake test data. They note that in low-level testing the distribution of transducers is becoming more extensive than before. They state that a logical extension of this would be to use system identification methods for determining the optimal locations of the transducers. Regarding the analysis of earthquake-response data, they point out the need for characterizing nonlinear elements of the system and for assessing structural damage. They consider ambient tests to be a useful means for determining whether a given structure can be occupied prior to detailed inspection and possible repair after a severe earthquake. They also observe that usually there is a large variability in the results of data analysis and that there is a need for including an estimation of variability of the results.

The comparisons reviewed above demonstrate both the value and the limitation of dynamic tests as a means for predicting the response to strong-motion earthquakes. The major finding that emerges is that if large civil engineering structures are modeled as linear systems, then it should be recognized that their modal parameters could show large variations not only between low-level tests and earthquakes, but also during various phases of the earthquake.

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The periods generally increase from low-amplitude, pre-earthquake test values by as much as 20-50% during earthquakes that hardly caused any structural damage. Housner and Jennings (Ref. 23) note that the increase in the pre-earthquake, test-measured period for buildings can be much larger (by as much as a factor of two or three) during strong earthquake motion that causes some structural members to yield. (In the extreme case of a structure that collapses, its fundamental period, of course, goes to infinity.) Damping also generally tends to increase from tests to earthquakes, though this trend has not always been uniform. The substantial changes in the modal parameters from tests to earthquakes indicate that such parameters determined from low-amplitude tests may not be applicable for calculating response to strong-motion earthquakes. Yet one has to note that but for the performance of dynamic tests at various amplitude levels, coupled with earthquake-response measurements, the nonlinear trends would remain even more obscure than they are now.

Another point to be noted is that, despite the knowledge that modal parameters vary with time and amplitude, the models identified from both tests and earthquakes are almost always time-invariant or time-varying linear models. This is mainly due to the lack of availability of widely applicable nonlinear models for the soil-structure system and the appealing simplicity of the linear models.

Regarding the actual methods used in dynamic testing procedures and earthquake-response analyses, it is seen that the instrumentation has not generally been as extensive in response measurements during earthquakes as during tests. While the reason for this is obvious, this lack of more than one or two earthquake records from a complex structure makes it difficult to identify more than one or two lower modes from the earthquake-response data. It has been noted, further, that any particular earthquake may not excite all the important modes, i.e., even some of the lower modes. The methods used for parameter estimation from earthquake response may not have given reliable results, as many of them are based on statistical assumptions not generally satisfied by earthquake-response records. Damping estimates from earthquake response are generally not considered reliable. For these reasons, some of the results of the comparisons reviewed should only be considered as tentative. More data collected from low-level tests, more extensive data on response to many earthquakes, and better parameter-estimation methods are all needed before these tentative conclusions are confirmed.

3. PROGRAM PLAN

3.1 HDR Cooperation

Argonne National Laboratory is the NRC coordinator for this effort. The HDR facility is a modification of a superheated steam reactor that was decommissioned and modified for research in 1973. A series of experiments (called Phase I tests) was conducted during 1975-1983, involving experiments on materials engineering, thermal hydraulics, and mechanical and earthquake

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engineering. The primary focus of the experiments was comparison of predictions by analytical models with experiments. The Phase II experiments, during 1984-1988, are similarly motivated and will examine higher levels of response where damage to structures, systems, and components is expected. NRC participation in the seismic tests will involve providing predictions for the response of structures and piping systems excited by shakers. One series of experiments, in which the containment building was excited by a large shaker, was completed in June-July 1986. Another series in which piping systems will be excited into the inelastic range by servo-hydraulic shakers is planned for February-March 1988.

1. HDR System

The Federal Ministry for Research and Technology (BMFT) decided to use the HDR superheated steam reactor for safety research in 1973. It is a 100 MWTH experimental reactor built to demonstrate the feasibility of direct nuclear superheating. The plant, designed in 1967-1968, suffered extensive fuel element damage after less than 2,000 hours of operation.

In order to carry out safety experiments, the plant was decommissioned and a new safety loop built that enabled the plant to simulate BWR and PWR operating conditions. Decommissioning work included dismantling and removing all activated components and equipment no longer needed. Plant modifications included the addition of systems to introduce heat to bring the whole test loop to pressure and temperature. For this purpose, a 4 MW electric boiler is connected into the loop. Water circulation takes place by means of the former primary circuit partial-load pump.

Extensive recabling was carried out to provide instrumentation and electrical power lines protected from blowdown conditions. A Central Data Acquisition System (ZMA) and amplifiers were installed in the control room.

The HDR facility lies on the River Main approximately 50 km east of Frankfurt. The first German nuclear power station (VAK) and a conventional power station are immediately adjoining. Figure 1 is a cutaway view of the HDR facility showing various features of the plant and attached structures. Plant dimensions, design pressures, and volumes are tabulated in Table 1. Table 2 contains other technical data for test loop operations.

2. HDR Program

The HDR safety program has been under way since 1975 and covers all components important to the safety of light water reactors (LWRs) such as:

- Containment
- Containment structures
- Reactor pressure vessel
- Internal fittings to the pressure vessel
- Piping systems
- Valves

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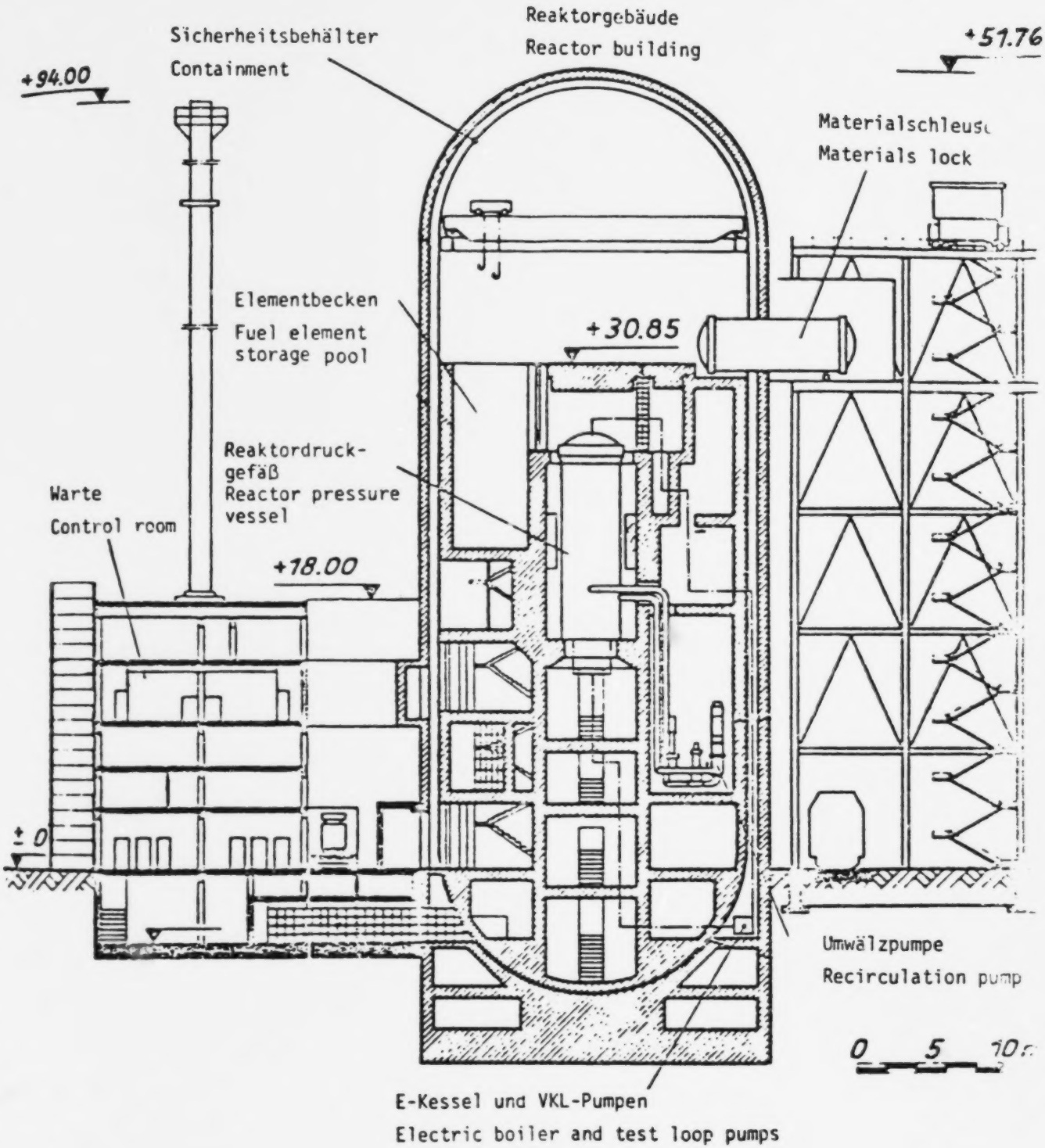

Figure 1 Reactor Building Vertical Sections.
(Provided by KfK.)

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Table 1 Principal Design Data for HDR Plant.
(Provided by KfK.)

Design data pressure vessel	Containment	RPV	Pressurizer (HDU)	Subcooler	Dimension
Height	60	12.70	14.11	4.365	m
Inside diameter	20	2.96	1.765	0.7	m
Wall thickness	17/30	112	45	28	mm
Design pressure					
-- overpressure	5.60	110	110	110	atm.g.
-- underpressure	350	-	-	-	mm wat.col.
Test pressure	7.12	-	-	-	atm.g.
Design temperature	155	360	550	320	^{o}C
Material	Fine-grained steel FB 50 S	23 NiMoCr 36	BHW 38	BH 395	-
Free volume	13349	-	-	-	m^3
Flow: primary	-	-	-	170	t/h
secondary	-	-	-	130	t/h
Data for HDR water circuits	**Heater circuit**	**Cooling circuit**	**Recirculation circuit**	**Spray system: 3 spargers with 45 jets**	
Design pressure	120	120	112	180m wat.col.	atm.g./m wat.c
Design temperature	324	324	320		^{o}C
Material	No.1.4550: 15Mo3	No.1.4550: 15Mo3	No. 1.4550	-	-
Nominal bore	150-250	150-250	350-450	80	mm
Capacity	40-90	90-190	1400-1600	100	t/h

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Table 2 Technical Data for HDR Test Loop.
(Provided by KfK.)

No.		Units	BWR operation	PWR operation
1	Boiler power	MW_{th}	3.5 const.	3.5 const.
2	Pressure in upper RPV region	atm. abs.	40.56 - 90	110
3	Temperature downstream of electric boiler	^{o}C	250 - 302	250 - 310
4	Enthalpy downstream of electric boiler	kcal/kg	259.2 - 323.6	259.2. - 334.3
5	Capacity $\dot{m}_k$ of primary circuit half-load pump (boiler throughput)	t/h	40 - 90	40 - 90
6	Mixed temperature t_m in lower RPV region	^{o}C	180.5 - 276.1	180.5 - 284.2
7	Mixed enthalpy h_m in lower RPV region	kcal/kg	183.9 - 290.1	183.9 - 300
8	Capacity $\dot{m}_{ws}$ of primary circuit full-load pump (heat sink)	t/h	90 - 190	90 - 190
9	Cold water temperature t_{ws} downstream of both subcoolers (heat sink)	^{o}C	148 - 264.1	148 - 271,3
10	Cold water enthalpy h_{ws} downstream of both subcoolers (heat sink)	kcal/kg	150.5 - 274.3	150.5 - 284.1

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The principal objectives of the investigations concerning plant structures, systems, and components are:

- Improvement of the understanding of the properties and structural behavior of these systems and components in specific incidents relative to safety and quantification of the available safety margins.
- Demonstration of the reliability of design methods and inservice inspections of these components.
- Optimization and improvement of analytical techniques.

Phase I of the HDR safety program was concluded in 1983. This phase involved testing beginning at low levels with tests increasing in severity but not so high that an early failure would put later tests in question. Phase II includes tests that will deliberately weaken or damage some of the HDR facilities.

Phase I Earthquake Investigations (EV 4000) comprised three different types of low-level excitations of the HDR containment building and additional medium- and high-level excitations of certain piping systems. In different series of tests the containment building and certain subsystems were excited with (a) a pair of rotating eccentric mass vibrators placed on the operating floor and producing a steady-state sinusoidal force in the desired direction, or (b) impulse forces (100 to 400 kN) produced with reaction rockets mounted normal to the hemispherical dome of the building or (c) the detonation of small (5 to 10 kg) explosive charges buried at distances of about 30 m from the center of the building. Additional tests on the piping system involved shaker excitation directly applied to the piping system and snapback tests.

Phase II includes high-level testing in several areas. These are Pressurized Thermal Shock, Piping Failure Tests/Pipewhip, Piping Stress under Blowdown, Containment and RPV Blowdown, and Earthquake High-Level Tests. The tests useful for seismic PRA validation are the Earthquake High-Level Tests. The main objective of the Phase II earthquake tests is to provide high-level excitation to the building and mechanical equipment in the HDR facility. The excitation simulating the earthquake motion is to be provided by a large shaker at the operating floor level of the reactor building and additional shakers as needed for excitation of the piping, polar crane, and other components. A breakdown of the EV 4000 Phase II test groups is shown in Tables 3 through 6.

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Table 3 PHDR Phase II Test Groups (Subproject EV 4000).
(Provided by KfK.)

No.	Test Groups / Test Parameters	Investigations / Tests Experimental Objectives	Desired Result of Data / Calculation Comparison	Remarks
1	Shaker Tests at RCE "SHAG" High excitation level for reactor building,	b) Load Analyses (Stress analysis and structural behavior): - structural non-linearities - load propagation in building - transfer behavior of concrete→ components - component loads - soil-structure interaction - damping of structure, soil, components	Verification of analytic techniques for load propagation, component loads, soil-structure interaction	
2	Shaker Tests at Mechan. Equipm. "SHAM" • Pipe and vessel investigations in the inelastic regime. . Test loop (VKL) . Superheated Steam Generator (HDU) . Vessels on resonance level (BER) . Floodwater storage tanks (FWB)	- reaction and stresses of pipes and vessels under extreme dynamic loads (plastification) - damping, as a function of load, frequency, material, preexisting damage - hanger influences - coupling/decoupling	Verification of non-linear analytic techniques, simplified techniques (RSMA with ductility)	Relationship to EV 2000 test groups "ROBL" and "ROV" (see Appendix A)
3	• Pipe investigations in frequency regime >20 Hz, and with high forces on main steam line or VKL	- behavior of pipes under aircraft impact loads - damping, as a function of load and frequency - evaluation of support clearance in upper frequency regime	Verification (also simplified) analytic techniques for component design against aircraft impact, verification of structural dynamics models for blowdown calculations	Nos. 2 and 3 to be eventually combined in one group

Table 4 PHDR Phase II Test Groups (Subproject EV 4000)
Impulse Excitation of Containment Outer Shell.
(Provided by KfK.)

No.	Test Groups / Test Parameters	Investigations / Tests Experimental Objectives	Desired Result of Data / Calculation Comparison	Remarks
4	Impulse Excitation of Outer Containment Shell ("STO ") - impulse excitation with successively higher loads (100 ms, 160 kN-sec) - operating conditions "cold" and "hot" (70 bar, 285 °C) - local loading of outer containment shell	Simulation of Aircraft Impact b) Load analysis: - global effects of local loading . follow load propagation in building/auxiliary building/free field . component loading - damping: structure, soil, components	Verification of analytic techniques for aircraft impact: - safety margin - structure design - component design	- investigations of local behavior in impact zone excepted - safety analyses against local failure necessary

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Table 5 PHDR Phase II Test Groups (Subproject EV 4000)
Crane Slip Tests. (Provided by KfK.)

No.	Test Groups / Test Parameters	Investigations / Tests Experimental Objectives	Desired Result of Data / Calculation Comparison	Remarks
5	Crane Slip Tests ("RUK") Test method: horizontal RGE shaker, vertical shaker mounted on crane; simultaneous shaking	b) Load analysis (structural dynamics reaction) - slip displacements of the crane - impact forces of the slipping crane - general vibrational response	Demonstrate safety of containment building (and crane) for external loads	

Table 6 PHDR Phase II Test Groups (Subproject EV 4000)
Seismometer Measurements Under Environmental Noise.
(Provided by KfK.)

No.	Test Groups / Test Parameters	Investigations/Tests Experimental Objectives	Desired Result of Data / Calculation Comparison	Remarks
6	Seismometer Measurements under Environmental Noise Excitation ("RAU") - HDR reactor building with known vibrational behavior	- Evaluation of actual vibration characteristics to verify the building model used to develop floor responses (excitation values for component response)	- Development of a systematic evaluation technique including statistical and probabilistic methodologies - Development of a scheme for optimized design of measurements over the estimated calculations of vibration behavior	
	- HDR components (e.g., RPV) with known vibration response	- Evaluation of actual vibration characteristics for verification of analytic models		
	- HDR structures and components with unknown vibration behavior Operating condition "cold", with and w/o water Long-term measurements ca. 1 hr	- Verification of the measurement- and evaluation methods	- Pre-calculation for special design of measurements - Evaluation of results and comparison with results from existing calculations and measurements	

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The centerpiece of these investigations is the high-level shaker tests (SHAG), which were performed at the HDR in June and July 1986. Their purpose was to investigate full-scale structural response, soil-structure interaction, and piping and equipment response under strong excitation conditions, i.e., under excitation levels that will induce significant strains in the structure and soil and produce nonlinear effects in the soil-structure system and piping. As with all HDR experiments, the primary intent is to use the SHAG tests to verify and validate calculational procedures and analysis methods. At the same time, the experimental data provide direct information on the response and performance of structural systems, piping, and equipment under high dynamic loading; such information may have direct applicability to understanding the behavior of nuclear power plant systems.

The shaker used in the SHAG experiments is a very large eccentric-mass coastdown shaker designed by ANCO Engineers, Inc., of Culver City, California. Most of the design and functional calculations of the shaker's dynamic behavior were performed by the Fraunhofer Institut fur Betriebsfestigkeit (LBF), Darmstadt, FRG. Safety calculations for the shaker, its mounting, and the HDR soil-structure system were performed by the engineering firms of Zerna-Schnellenbach in Bochum, FRG, and Hochtief AG in Frankfurt, FRG.

The masses of each of the two shaker arms (which form the eccentricity) are made up of an assembly of steel plates mounted on the arm base-plate and can be varied up to a total of 40 tons each. The shaker is capable of developing in excess of 1,000 tons of force. It is mounted in a very stiff frame on the operating floor of the HDR building (see Fig. 2) to provide strong excitation to the entire HDR soil/structure/equipment system. The shaker was designed to develop maximum accelerations of the HDR building on the order of 5 m/s^2 and maximum displacement of about ± 7 cm. The total eccentricity of the shaker was designed to vary between 4,000 and 145,000 kgm. During operation, the shaker is brought to the desired starting speed (1.6 - 8.0 Hz) with the two arms in a balanced condition. One of its arms is permanently fixed to the drive shaft, while the other arm is hinged to the shaft by a slightly eccentric support. In the balanced condition, the movable arm is fixed by an explosive bolt. After the desired starting speed is reached, the shaker arms are uncoupled from the drive system. Firing the explosive bolt releases the movable arm, which swings around and couples with the fixed arm, forming a large eccentric mass that provides a variable (in both magnitude and direction) force during coastdown. As the shaker coasts down through the fundamental frequencies of the HDR soil-structure system, strong resonances occur. During the entire shaker run, there is a strong coupling and feedback between HDR response and shaker forcing, resulting in a nonlinear coupled system.

As stated earlier, the purpose of the SHAG tests was to investigate full-scale structure-soil, equipment, and piping response under strong vibrational excitation and to validate predictive analyses. While the interests of PHDR and NRC/RES includes all aspects of the SHAG testing, most other participants focused primarily on the behavior of piping systems. In particular, the response of the VKL (Versuchkreislauf) piping systems with different multiple support (hanger) configurations was of interest to all participants.

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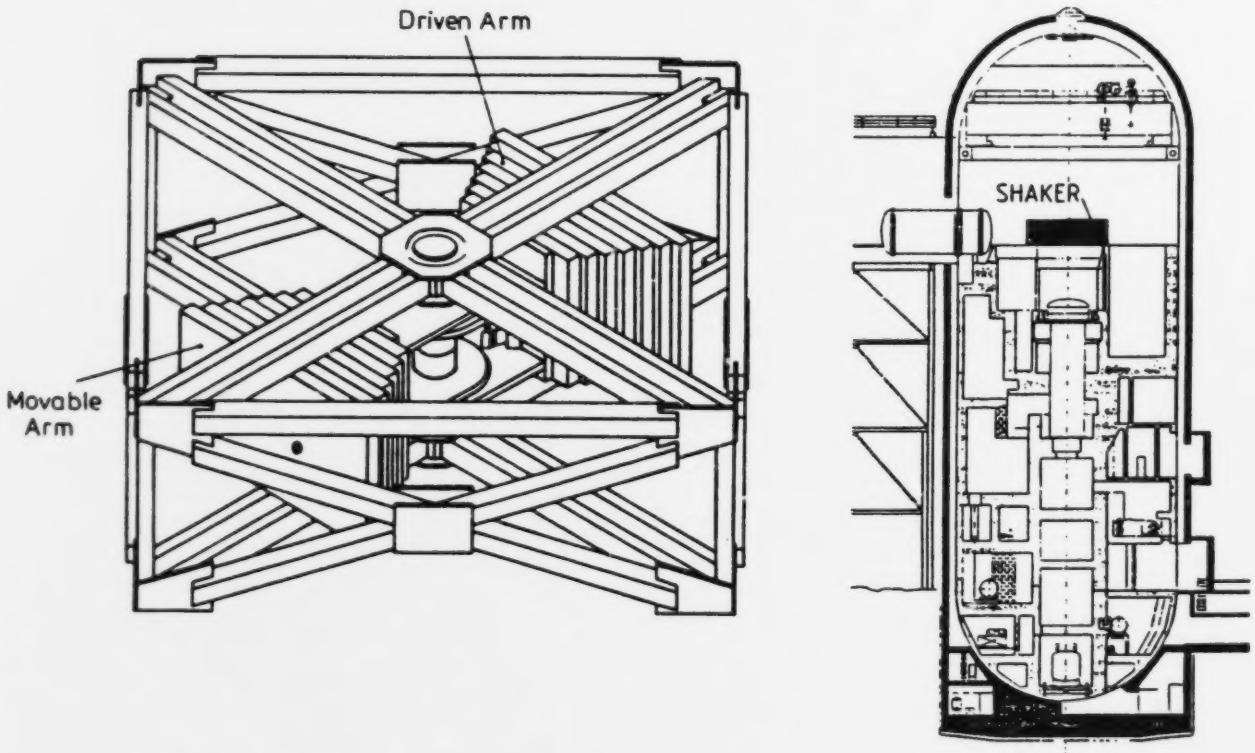

Figure 2 ANCO MK16 Shaker (Final Design).
(Provided by KfK.)

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The VKL piping (see Fig. 3) consists of a number of pipe runs ranging in nominal size from 100 to 250 mm rate. The piping is attached to the HDU vessel and associated manifolds and forms part of the experimental piping system at the HDR. The top of the pipe runs at about 28 m above ground level, just under the HDR operating floor (where the shaker is located). The original German hanger system provided primarily vertical deadweight support and consisted of 11 spring and constant-force hangers and one threaded rod. The original intent was to compare in the SHAG tests the performance of this very flexible conventional support system with a typical U.S. stiff support system containing snubbers and struts. Also, as part of the NRC/RES Equipment Qualification Research Program, the Idaho National Engineering Laboratory (INEL) intended to evaluate the performance of a typical U.S. gate valve during SHAG testings. Accordingly, an 8-inch valve was incorporated into the VKL piping system. INEL then designed a typical U.S. hanger system, adding six snubbers and six rigid struts to the VKL hanger system and replacing one of the German spring hangers with a much higher rated hanger of the same type to accommodate the added weight of the valve as shown in Figure 3.

EPRI and its industry associates intended to evaluate two additional hanger configurations. The first of these, designed by Bechtel Corporation, consists of energy-absorber supports that damp out the motion of the piping through the plastic deformation of an assembly of steel plates incorporated into the support. The other configuration uses seismic stops, designed by R. L. Cloud and Associates, that replaces the snubbers. This system allows free motion until a certain displacement is reached, at which the pipe impacts the stops, limiting further movement in the given direction. As part of German industry contribution to the SHAG experiments, Kraftwerk Union (KWU), Offenbach, FRG, designed a hanger system for the VKL piping, which uses, in addition to the deadweight supports, only five rigid struts placed so as to prevent large dynamic motions of the piping. All the alternative hanger designs of the VKL were motivated by the desire to replace snubbers, which have proved troublesome in nuclear power plants. Therefore, the objective of these experiments was to compare and evaluate the behavior of the VKL piping system with the different support systems under identical loading conditions.

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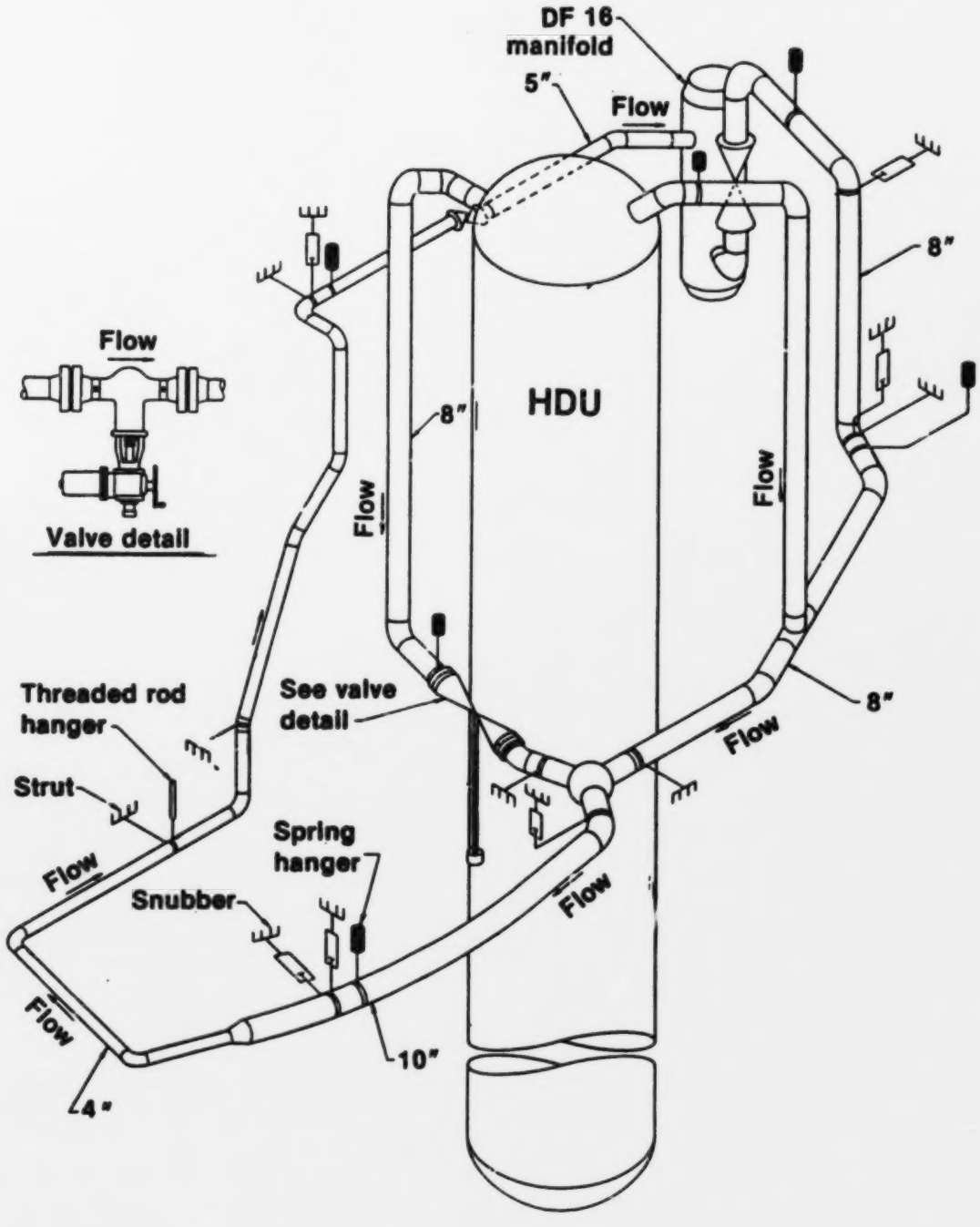

Figure 3 VKL Piping With U.S. Rigid Support System.

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With the agreement of all major participants, two more pipe support configurations for the VKL were added to the test matrix. One test each was planned for viscous damper supports of GERB, Berlin, and for modified viscous dampers designed by ANCO Engineers. Two of the GERB supports were used, while six of the ANCO supports replaced all snubbers in the U.S. NRC system. In order to avoid possible permanent damage to the VKL piping, the original HDR deadweight support system was modified by retaining the two rigid struts of the U.S. support system that are located adjacent to the spherical tee (see Fig. 3).

Additional safety calculations by Hochtief AG, as well as a "best estimate" soil-structure-interaction calculation and detailed stress analyses performed by Weidlinger Associates, Palo Alto, California, indicated that the 1.6, 2.1, and 3.1 Hz tests, when run at full load (10^4 kN), would provide a more severe challenge to the HDR structure than anticipated. Reexamination of the drawings also indicated lower capacity in the embedded region of the walls of the shield building. This led to a reordering of the test sequence, with the high-frequency tests for the piping being advanced in the schedule. Thus, while the first week of testing proceeded essentially as planned, in the second week of testing, 8.0 Hz experiments with three pipe hanger configurations were performed with the piping in cold conditions.

A test delay occurred at the end of the first week when Test 37 (at 2.1 Hz and less than half of full load) resulted in considerable shifting in a section of the outer shield wall (around the equipment hatch), which was made of concrete blocks. The concrete blocks had to be secured by a steel structure. Other delays came about because of interference from the VAK management and protests of antinuclear intervenors. All these problems necessitated reevaluation, inspection, and reapproval for further testing by the Technical Evaluation Agency (TUV) and the Licensing Agency of the Bavarian State Ministry. Hence, no tests were performed during the third week.

At the same time, the concern for the global integrity of the HDR structure necessitated a detailed evaluation of crucial test data (accelerations, displacements, and strains) after each test. These measurements were compared with predictions and estimates of structural capacity to guide the progress of experiments. All these factors caused the test period to extend to nearly 8 weeks. The tests actually performed and their sequence are listed in Table 7. As indicated, only the 8.0, 5.6, and 6.0 Hz tests were performed at or near full load (10^4 kN); all other tests were performed at reduced loads. Only the 4.5-Hz runs were performed with hot conditions in the piping system. All tests at 3.1 Hz and 2.1 Hz (at full load) were dropped to avoid challenging the walls of the outer shield building, which experience their most severe strains in the out-of-phase bending mode. The 1.6-Hz tests, which involves the rocking mode, were limited to a maximum of about two-thirds of full loads. All testing was completed on July 22, 1986. Detailed measurements of the response of the VKL piping and the performance of the 8-inch gate valve were carried out during nearly all experiments, except for the 1.6-Hz tests, which were conducted last (see Table 7).

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Table 7 SHAG Test Matrix--Performed.

RUN NO.	TEMP. °C	VKL SUPPORT SYSTEM	ECCENTRICITY in kgm	STATRING FREQ. in Hz	MAX. FORCE in kN	TEST WEEK
34	20	USNRC	4700	6	6600	
35	20	USNRC	4700	8	11800	1
36	20	USNRC	8200	5.6	10100	
37	20	USNRC	27800	2.1	4800	
40	20	EPRI/EA	4700	8	11800	
20	20	KWU	4700	8	11800	2
60	20	GERB	4700	8	11800	
						3
50	20	EPRI/SS	4700	8	11800	
70	20	ANCO	4700	8	11800	4
10	20	HDR	4700	8	11800	
30	20	USNRC	4700	8	11800	
31	20	USNRC	6450	6	9100	
41	20	EPRI/EA	6450	6	9100	
21	20	KWU	6450	6	9100	5
11	20	HDR	6450	6	9100	
51	20	EPRI/SS	6450	6	9100	
52	210	EPRI/SS	8200	4.5	6500	
32	210	USNRC	8200	4.5	6500	
42	210	EPRI/EA	8200	4.5	6500	6
12	210	HDR	8200	4.5	6500	
22	210	KWU	8200	4.5	6500	
12.1	210	HDR	8200	4.5	6500	7
14	20	HDR	33000	1.6	3300	
16	20	HDR	54000	1.6	5400	8
13	20	HDR	67000	1.6	6700	

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Ambient response measurement tests (RAU) were carried out before, during, and after the performance of the SHAG experiments. The RAU tests provide a measure of the changes in dynamic characteristics that occur in the HDR soil-structure system due to high-level excitation produced by the SHAG testing. The combined SHAG and RAU results will allow the investigation of nonlinear effects.

Pretest and blind posttest calculational predictions were performed by a number of organizations for many aspects of the SHAG tests. To allow for orderly completion of the posttest calculations, all experimental data are being held secure and will not be released until these calculations are completed. It is currently anticipated that at least the building response and soil-structure-interaction data will be released in 1987. The calculational efforts completed or in progress include predictions of the soil-structure interaction, building response (including stress analyses), and piping response. The piping response calculations are being done in the blind posttest mode and use measured building response as input.

The SHAG tests were planned to provide the maximum possible loading for the HDR soil-structure system and the piping without inducing global structure-soil failure, which would endanger the integrity of the containment. As indicated above, safety considerations for the HDR building necessitated some curtailment of the test plans. In particular, the test runs that strongly excite the main structural modes (out-of-phase bending nominally at 2.5 Hz and rocking nominally at 1.4 Hz) had to be reduced in load or abandoned. The major reason for this is the weakness of the outer concrete HDR shield building, whose cylindrical walls have very little reinforcement in the embedded region and which could thus fail in tension during bending.

In spite of the limitations imposed on the testing, the overall goals of the SHAG tests were accomplished. Peak accelerations and displacements in the HDR building were quite substantial and nonlinear behavior of the soil-structure system was clearly observed. Much local damage occurred, such as concrete cracking and interior masonry wall damage. Substantial amounts of energy were transferred to the surrounding soil, particularly during experiments challenging the rocking mode (1.6-Hz runs). This is evidenced by the high accelerations measured in the soil, cracking of soil (circumferential) away from the building, separation at the soil-structure interface, and soil subsidence. Impact occurred between the HDR building and the equipment tower as well as the connecting bridge to the office building. Strains in the HDR shield building walls approached or exceeded their estimated limit values. Accelerations and motions of the VKL piping measured in the SHAG tests are comparable with values expected during strong-motion earthquakes.

3. Role of HDR Tests in Seismic PRA Validation

The contribution to the testing needs for seismic PRA validation that will be made by the test data from the HDR safety program is discussed here. While the major emphasis is placed on the contribution of the high-level tests of Phase II, the use of Phase I data is also addressed where appropriate.

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The role of HDR to assist in validation of seismic PRA response-prediction accuracies can be a useful one. The HDR offers an integral structure-piping facility of significant complexity. This facility can potentially provide information on structure and piping responses of significant magnitude for comparison with seismic PRA predictions. The use of HDR can be expected to provide useful information on the degree to which the seismic PRA linear elastic analysis methodologies can predict load transmission and structure and piping response in a realistic situation where nonlinear effects and non-proportional damping is to be expected. Specifically concerning piping response, testing in the higher frequency range (above 20 Hz) is planned for Phase II HDR experiments. This information could be valuable to validate response predictions in a frequency range that appears to be an important component in Eastern United States earthquakes.

It should also be mentioned that significant information and insight concerning response analysis accuracies was obtained during Phase I HDR experiments. Thus, it was found that structural modeling details are not always necessary to capture the response, as long as the salient features are modeled. In fact, well-thought-out simple models often predicted with greater precision than more complex models. This aspect is very important for seismic PRA analysis simplification and can be further pursued during the Phase II HDR experiments. Finally, HDR test data should permit the evaluation of conservatisms and limits of applicability for the typical linear elastic analyses employed in seismic PRAs.

The HDR system was, during Phase I of the program, subjected to a variety of loadings in the low and intermediate range of excitations. The large shaker tests of Phase II will provide even higher multiple loadings. The system also is well instrumented. Thus, the application of the SMACS or similar methodologies to analyze a selected group of past and future HDR tests should provide good insight into the expected variability in response and physical properties of a complex reactor system. While it is realized that none of the HDR excitations are representatives of seismic excitation, such an exercise should, nevertheless, give good indications of how structural and component frequencies and damping vary with loading magnitude, type, and duration. Similarly, the HDR system could be used to test the effects of modeling variability by performing a number of analyses, each by a different analyst, for a single preselected test.

During Phase I of the HDR testing, significant insight into the variability of structural response parameters, such as damping, for both the HDR building and piping was obtained. This included both variations with load level and type as well as the statistical variability of these parameters under a given loading. This information will now be augmented in the Phase II tests with higher excitation level data. This information should be a valuable contribution to estimation of response variability.

The HDR facility also contains many equipment items that belong to single generic categories, e.g., valves. The possibility thus exists of obtaining quantitative information of the variability or dispersion of expected response in a generic group of equipment.

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The HDR offers an integral structure-equipment system of significant complexity. It is thus likely that response correlations during high-level loadings will occur. This holds particularly for correlations arising from the structural configurations. The use of HDR data for establishing the expected correlations will therefore be explored.

Safety considerations for the HDR containment integrity preclude the possibility of liquefaction or significant soil failure during testing in the direct vicinity of the building. Thus no significant validation of seismic PRA methods in this area is possible. On the other hand, the HDR site is relatively soft, has a high water table, and its properties are well documented. This provides an opportunity to evaluate both the adequacy of the viscoelastic soil modeling and the construction of impedance functions used as part of typical soil-structure-interaction analyses. It should also be noted that the HDR site contains a recompacted soil region in the vicinity of the HDR building. Preliminary calculations by German investigators indicate that, at the boundary of this region and the undisturbed soil, sufficient straining may occur during the large shaker experiments to approach liquefaction conditions. The usefulness of this information for validating soil response predictions in seismic PRA analyses should be explored.

3.2 NUPEC Cooperation

Brookhaven National Laboratory is the NRC coordinator for this effort. A massive testing effort was started in 1974 under the sponsorship of the Japanese Ministry for International Trade and Industry (MITI). The Nuclear Power Engineering Test Center was established and the largest shake table facility in the world was constructed at the Tadotsu Engineering Laboratory. The table is 15m x 15m with a capacity of 1,000 tons. Characteristics of the table are shown in Table 8 (Ref. 24). (For purposes of comparison, the largest shake table in the U.S., operated by the Richmond Field Station of the University of California, is 6m x 6m with a capacity of 60 tons.) The test series, during 1982-1988, will involve eight specimens representing containment vessels, primary loops, reactor pressure vessels, and reactor internals for both PWRs and BWRs. The test specimens are depicted in Table 9 (Ref. 25). All specimens will be excited with time histories representative of the Japanese design earthquakes, designated S_1 and S_2, and similar in intent to our OBE and SSE. Responses to those motions will be monitored. The series is known officially as the "Seismic Proving Test Programme."

NRC's main interest is in the ability of analytical methods to predict the onset of component damage under very large earthquake motions. To that end, we have negotiated for tests to be performed after "proving tests" have been completed on one specimen, a PWR piping loop model. We, and the Japanese, anticipate that the specimen will respond elastically to the proving tests and will be in an undamaged state. The tests in which NRC will cooperate involve increasing the excitation (within the limits of the table) and modifying the specimen to induce inelastic response. Possible modifications under discussion include both adding mass and removing one or more supports. The PWR piping loop test will be performed in 1988. The 1/2.5-scale test model with its

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Table 8 Main Performance of Vibration Table.

Item		Performances	Remarks
(1) Maximum Loading Capacity		1,000 ton	
(2) Table	Size	15m × 15m	
	Weight	600 ton	Including movable parts of exciting mechanism
(3) Excitation Directions		X·Z Axis simultaneously	X: Horizontal Z: Vertical
(4) Maximum Stroke	Horizontal	±200mm	
	Vertical	±100mm	
(5) Maximum Velocity	Horizontal	75cm/s	
	Vertical	37.5cm/s	
(6) Maximum Acceleration	Horizontal	2,670 Gal 1,800 Gal	500t Inertia load 1,000t Inertia load
	Vertical	1,335 Gal 900 Gal	500t Inertia load 1,000t Inertia load
(7) Excitation	Horizontal	3,000 tonf	
	Vertical	3,300 tonf	
(8) Permissible Overturning Moment		6,500 tonf-m	To satisfy at the time of maximum vertical excitation
		12,000 tonf-m	No vertical excitation applied
(9) Permissible Yawing Moment		3,000 ton-m	
(10) Duration of Excitation		20 sec.	Simultaneous two-axis excitation (at maximum speed sine-wave)
(11) Continuous Excitation		5% of maximum speed	Simultaneous two-axis excitation
(12) Frequency Range		0-30 Hz	

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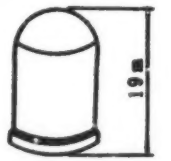
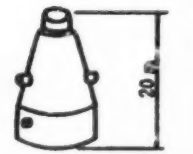
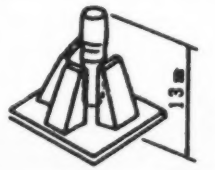
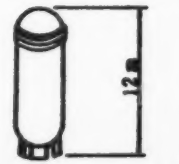
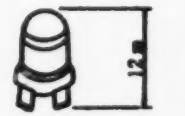
Table 9 Aseismic Proving Test Model.

TYPE / ITEM / COMPO-NENTS	P W R				B W R			
	ACTUAL WEIGHT	SCALE	MODEL WEIGHT	SIZE	ACTUAL WEIGHT	SCALE	MODEL WEIGHT	SIZE
CONTAINMENT VESSEL	3,800 t	1/3.7	340※1		3,500 t	1/3	350※1	
PRIMARY COOLANT LOOP	1,000.	1/2	280※		800	1/1	665※	
REACTOR VESSEL	800	1/2	280※		800	1/2	290※	
REACTOR INTERNALS	500	1/1	440※		500	1/1	380※	

※ NOTE : INCLUDING SUPPORTING STRUCTURE

support structures is depicted in Figures 4 and 5. As can be seen, the model consists of a steam generator, a coolant pump, and three sections of the primary piping system, i.e., the hot leg, the crossover leg, and the cold leg. The reactor vessel is not included because the piping-reactor connection is assumed to be fixed or rigid. Dimensions of the piping section are given in Table 10 and Figure 6.

3.3 EPRI Cooperation

While much effort has been devoted to the development of seismic soil-structure-interaction (SSI) analysis methods, relatively little has been done to verify these methods with seismic experimental data, i.e., structural and site response data recorded during natural earthquakes. Among the few notable exceptions is the work by Seed and Lysmer (Refs. 26 and 27), which included comparisons of analytical predictions with measurements recorded in the Humboldt Bay Nuclear Power Station during a strong-motion earthquake. In general, the assumptions and approximations in the various SSI analysis methods used in the design, licensing, and risk assessment of nuclear power plants and the uncertainties they introduce into the results have not been systematically investigated vis-a-vis recorded data obtained specifically for this purpose. To remedy this situation, both the NRC and the Electric Power Research Institute (EPRI) have undertaken programs for the validation of SSI analysis methods using experimental data that include motions recorded during natural earthquakes. A cornerstone of these efforts is the EPRI/NRC cooperation in the seismic experiment with scale-model containment structures built in Lotung, Taiwan, within the SMART-1 array.

The objective of the experiment is to verify or assess analytical predictions of important SSI aspects with extensive seismic ground-motion and structural response data collected over a period of years at a site where strong-motion events are known to occur frequently. Modeling techniques for site response, foundation input motions, and response of the structures and subsystems are among the major issues that will be subjected to verification. In addition to natural earthquakes, the model structures were subjected to dynamic testing with steady-state excitation to obtain baseline dynamic characteristics of the systems just after construction and before the occurrence of any strong-motion earthquake.

The validation process consists of blind predictions of site and structural response to the dynamic test excitation and to a selected strong-motion seismic event, and subsequent comparison of predictions with corresponding measurement records. Different methodologies, varying from the relatively simple to the state of the art, are used by different analysts to make the predictions. The predictions and comparisons will be made in distinct phases. In each phase, the same input data are provided to all the analysts, independent models are devised, and blind predictions are made. After the predictions are completed, the analysts are provided with measurement data with which they perform comparisons. If the event modeled is the dynamic test, the comparison may lead to an improved model in the subsequent phase in which seismic response is predicted.

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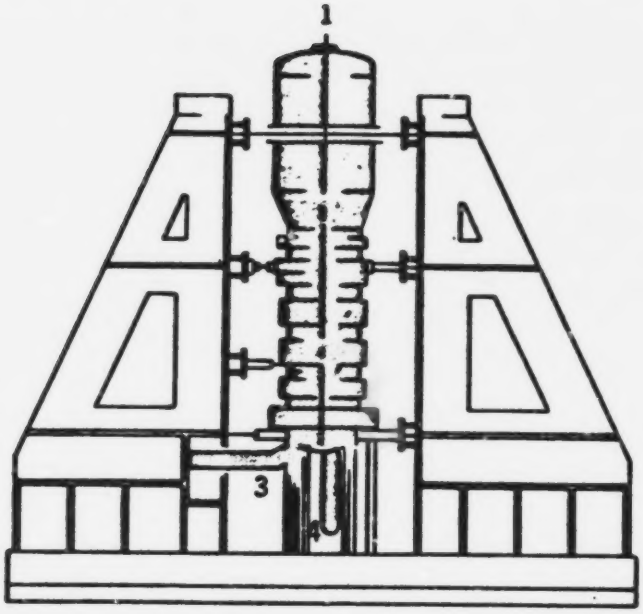

LEGEND:

1 - steam generator
2 - reactor coolant pump
3 - hot leg pipe
4 - cross over leg pipe
5 - cold leg pipe
6 - lateral supports
7 - support frame

Figure 4 Proving Test Model of PWR Coolant System With Support Structures (Front View).

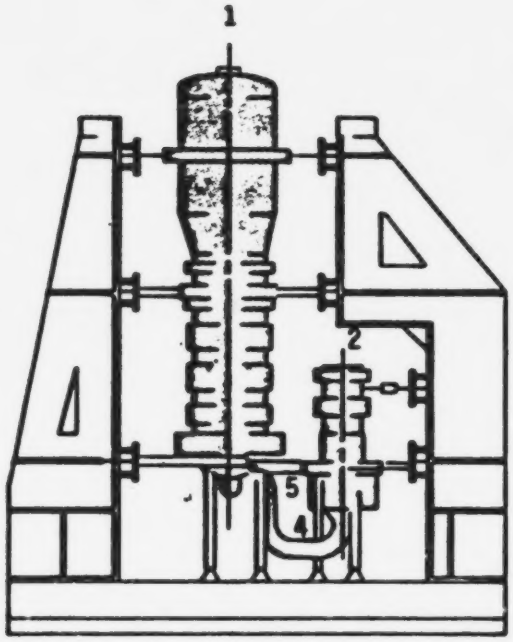

Figure 5 Proving Test Model of PWR Coolant System With Support Structures (Side View With Coolant Pumps).

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Table 10 Specification of Piping System.

	Unit	Hot Leg		Cold Leg		Cross-over Leg	
		Straight	Bend	Straight	Bend	Straight	Bend
Outside Diameter	cm	35.3	38.1	33.5	35.0	37.7	39.4
Thickness	cm	2.9	3.4	2.8	3.2	3.1	3.5

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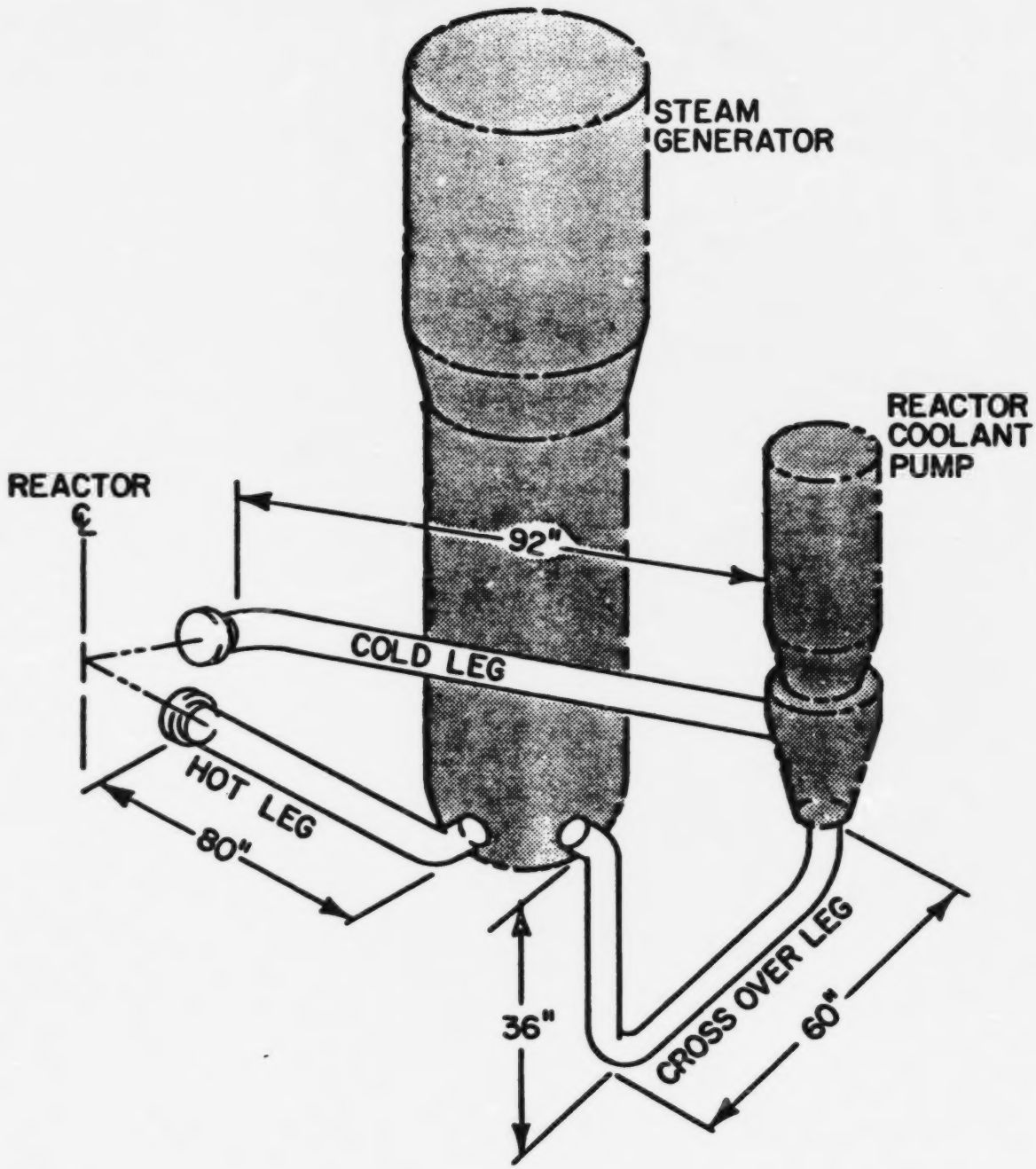

Figure 6 Isometric Schematic of PWR Coolant System.

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EPRI, in cooperation with the Taiwan Power Company (Taipower), has built two scale-model (1/4- and 1/12-scale) concrete containment structures in Lotung, Taiwan. The site is located in a highly seismic region and is within an NSF/U.S. Berkeley array of strong-motion seismographs, the SMART-1 array (Ref. 28). The SMART-1 array consists of a central element and three concentric circles, each with 12 surface seismographs, with radii of 200 m, 1 km, and 2 km, respectively. The 1/4-scale EPRI model is located between the outer and middle circles of the array (Fig. 7). From October 1980 (soon after the installation of the array began) through May 1984, 29 earthquakes with local magnitude ranging from 3.8 to 7.3 were recorded by the SMART-1 array (Ref. 29). Of the first nine, three were located directly below the array at focal depths of 59 to 76 km; the other six had shallow depths and epicentral distances from 7 to 193 km (Ref. 28). Thus, experience has shown that the site selected for the experiment is ideal for the collection of seismic data.

The soil at the site mainly consists of saturated sandy silt and silty sand with a shear wave speed in the range of 500-1,000 fps. During the design stage, the results of a seismic refraction survey of the SMART-1 area (Ref. 29) became available. More detailed data from additional site exploration and laboratory soil testing have since been obtained and will become available to the analysts for analytical modeling. Figure 8 shows a cross section of the 1/4-scale containment structure and its major dimensions. A scaled steam generator and piping loop are installed inside the building. The structure is not a replica model of a typical nuclear power plant containment building. The massive roof slab was necessary to ensure that the fundamental frequencies of the model fall within the frequency range of seismic excitation typical of the region. This program is not intended to scale up the measured response to a prototype containment structure. Soil-structure interaction is expected to occur during earthquakes and the measured responses will be directly used for verifying predictive methodologies.

The purpose of the low-level vibration tests--sponsored by NRC--was to define the dynamic characteristics of the soil-structure system in an as-built condition before the system was subjected to strong-motion events. The results of the tests are to be first predicted by the analysts and subsequently to be used for refining the first stage; the tests were performed with only the basemat completed. Since the water table was very close to the ground surface, water was pumped from the excavation during these tests. In the second stage, the tests were performed on the completed structure. The excavation was backfilled, and the sheet piles were removed before the start of the second-stage testing.

Subsequent to the performance of tests, all the response data were normalized to a constant force of excitation. The data were evaluated by Argonne National Laboratory for their quality, and most of the data were found to have sufficiently high signal-to-ratio. The response data from the basemat tests were used to determine the following experimental soil impedance functions: vertical, K_v; torsional, K_t; sliding, K_h; rocking, K_r; and coupled sliding-rocking, K_{hr}. Approximate values of the resonant frequencies of the fundamental modes of the basemat were estimated by inspection of the data. The

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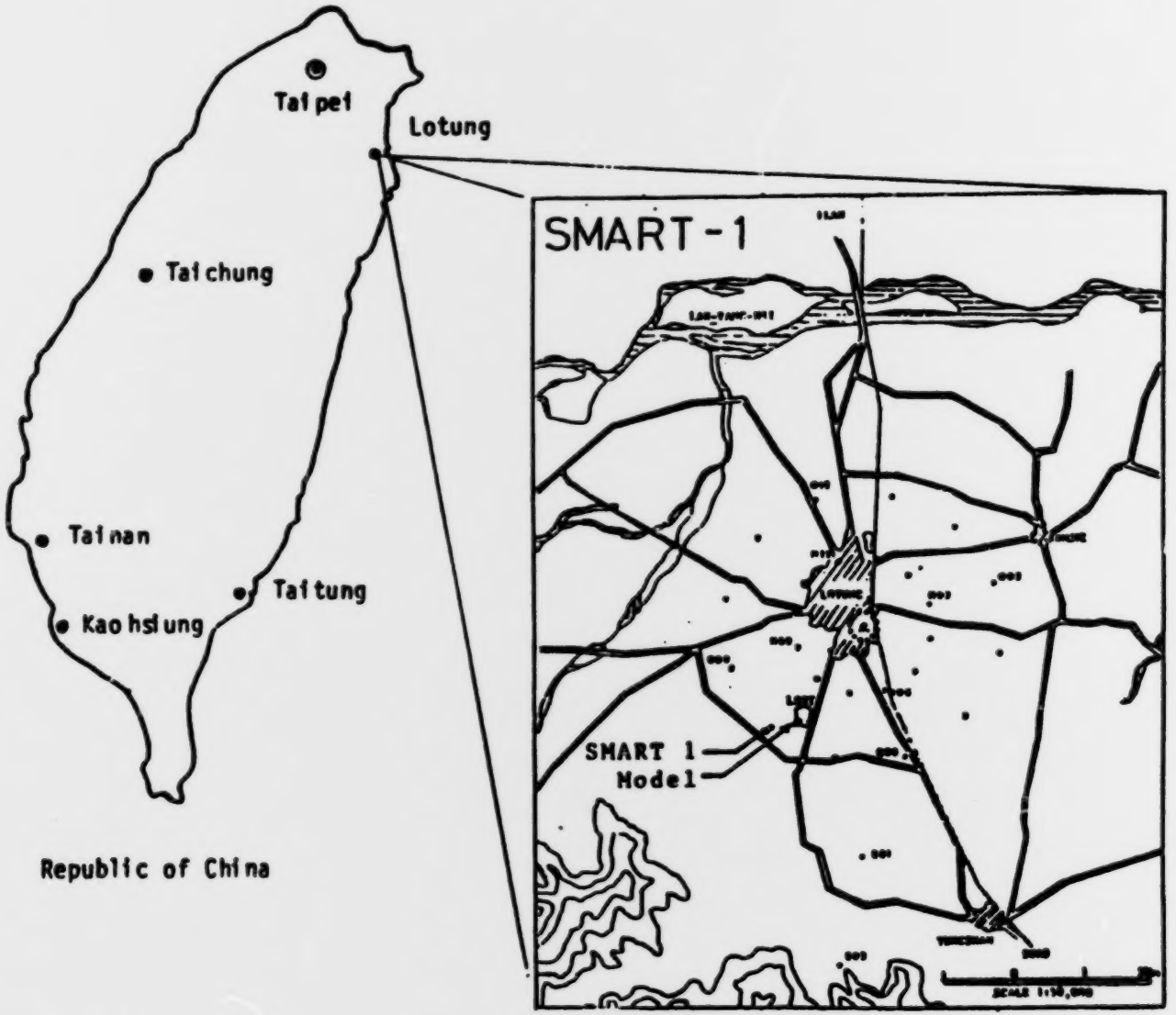

Figure 7 Test Site Location in Taiwan.

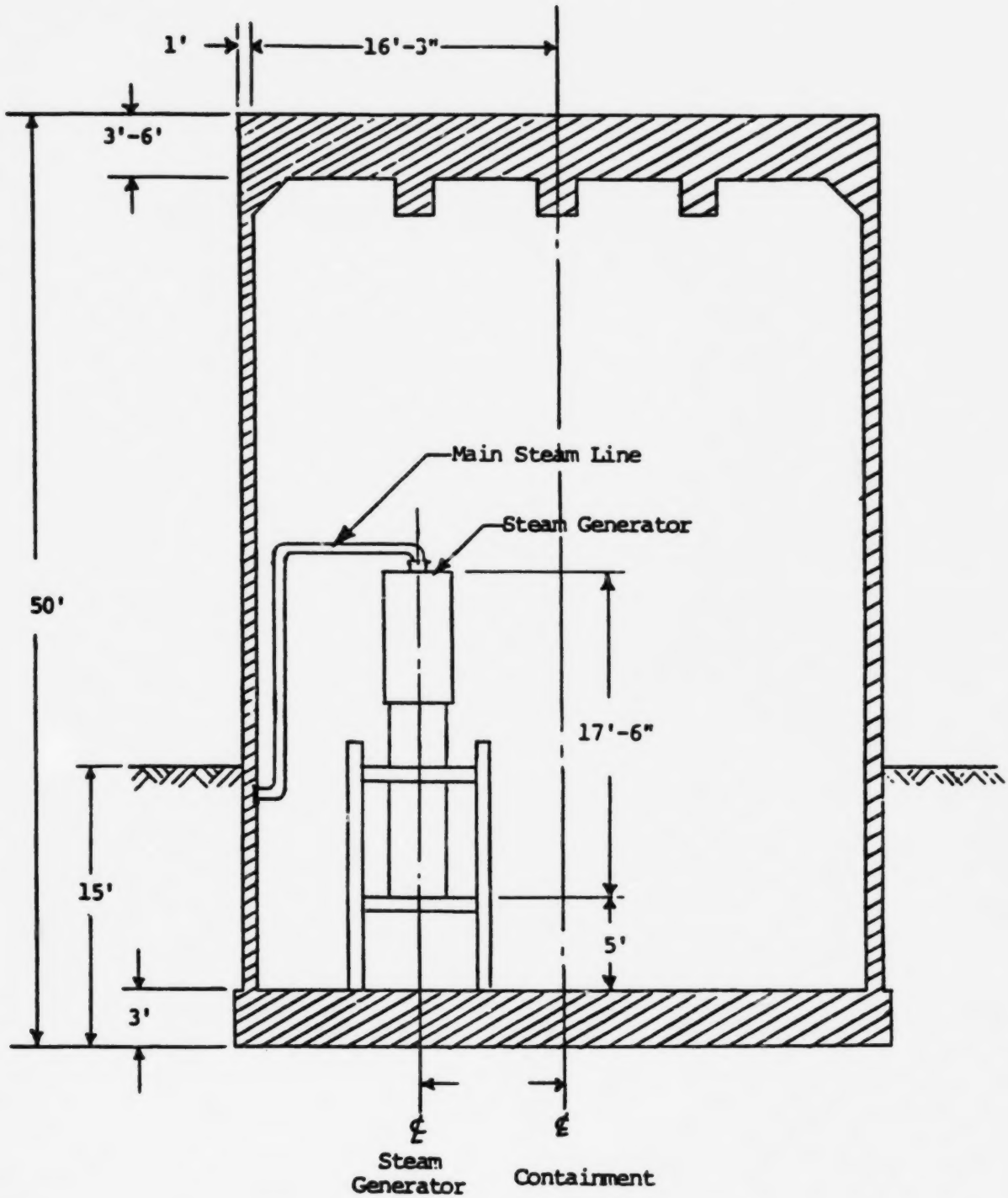

Figure 8 Cross Section of 1/4-Scale Containment Model in Taiwan.

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response data from the completed structure were used with the modal identification software of an HP 5451C system to determine a modal model of the system. The modal model consists of estimates of the lower natural frequencies, modal damping, mode shape vectors, and modal mass.

Since the validation plan also includes blind predictions of the vibration test response, the results obtained from the above-noted analyses, performed at Argonne National Laboratory, will be published only after the completion of the predictive calculations that are being performed by various analysts at present.

It should be noted that EPRI added six accelerometers to the piping system inside the model containment structure during the vibration tests. Also, independent low-level impact tests were performed on the piping system to define its dynamic characteristics.

Soon after the completion of construction (by the end of October 1985), all seismic instrumentation was installed by the Institute of Earth Sciences, Academia Sinica, who are responsible for maintaining, collecting, reducing, and analyzing the seismic response data for Taipower and EPRI. Ground-motion measurements on the surface and downhole in the field and response measurements of the structure are made with triaxial strong-motion accelerometers. In addition, interfacial pressure transducers measure the contact pressure between the containment structure and the surrounding soil.

The surface instrumentation installed in the field consists of an array of three arms, as shown in Figure 9. Each arm contains five stations and in each station the accelerometer is set on a concrete pad and is enclosed by a fiberglass housing. The downhole instrumentation consists of two vertical arrays, aligned along arm 1 of Figure 10, and located as shown in Figure 10. Each vertical array has four downhole accelerometers at different depths, as indicated in Figure 10.

The structural instrumentation of the 1/4-scale containment model consists of 10 accelerometers installed inside the containment structure. Of these, four are installed at the base, four at the top below the roof slab, and one each at the base and at the top of the model steam generator. The schematic of the structural instrumentation is shown as Figure 11.

The interfacial instrumentation of the 1/4-scale containment structure consists of 13 pressure gages, as shown in Figure 12. Eight of these are buried underneath the basemat with two gages for each principal direction. Of the remaining, three are mounted below ground level along a vertical axis on the outside of the wall in the north side, and two are similarly mounted in the west side.

Since the model was completed in October 1985, the EPRI Lotung experiment has recorded more than a dozen seismic events. The recorded earthquakes ranged from magnitudes 5.3 to 6.5 (Richter scale) with epicenter distances varying

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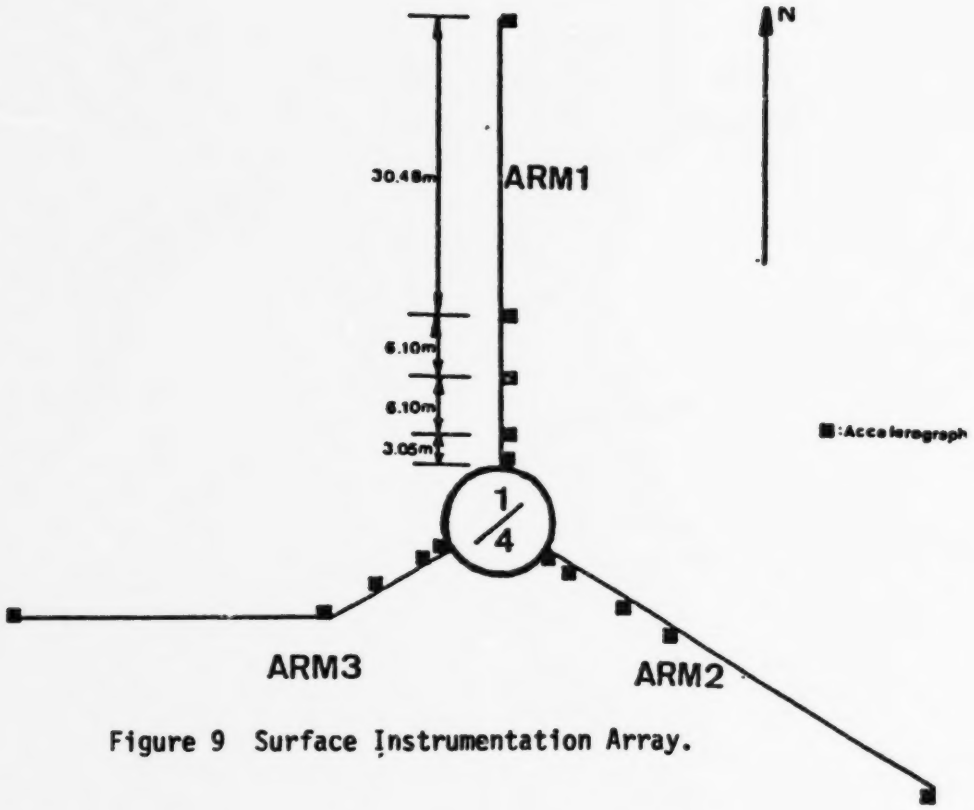

Figure 9 Surface Instrumentation Array.

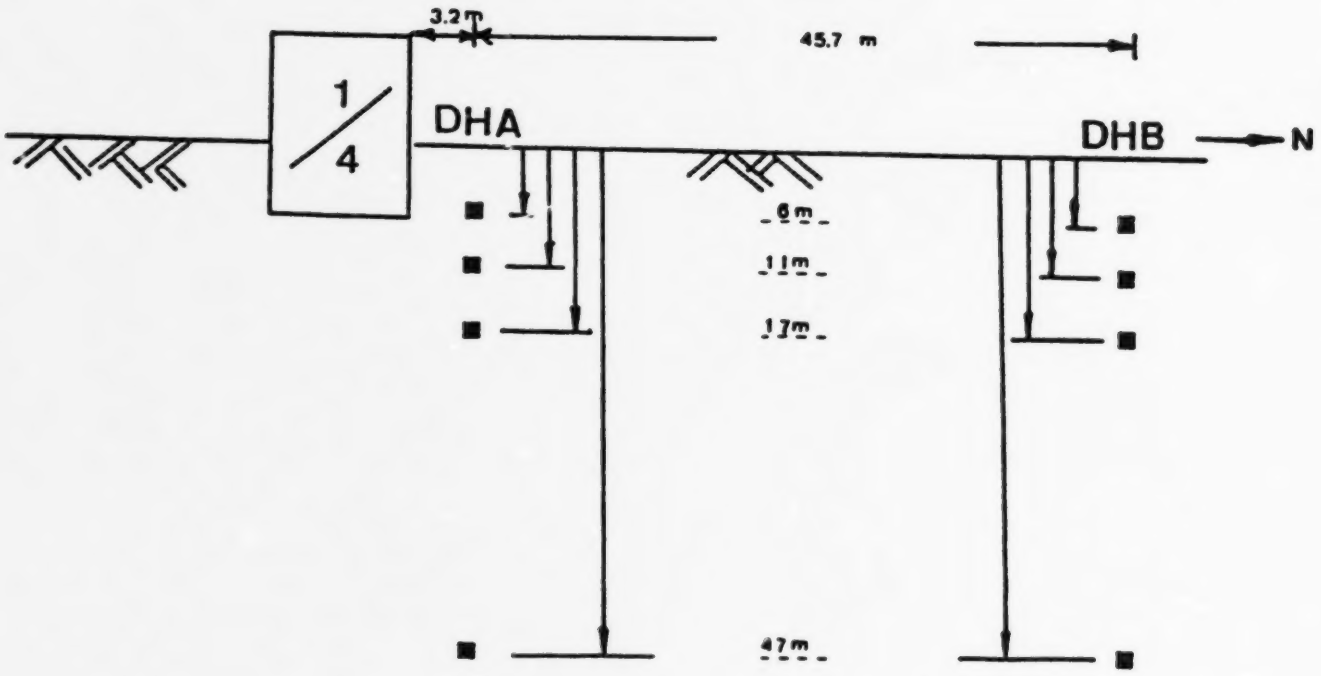

Figure 10 Downhole Instrumentation.

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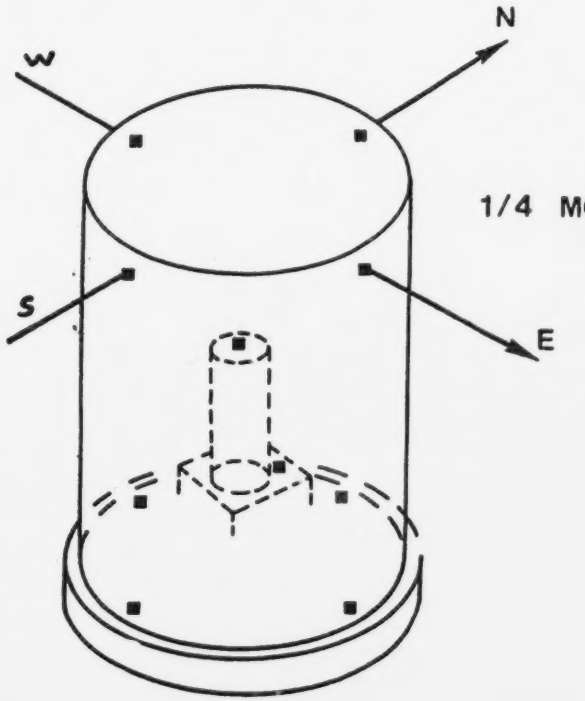

Figure 11 Structural Instrumentation.

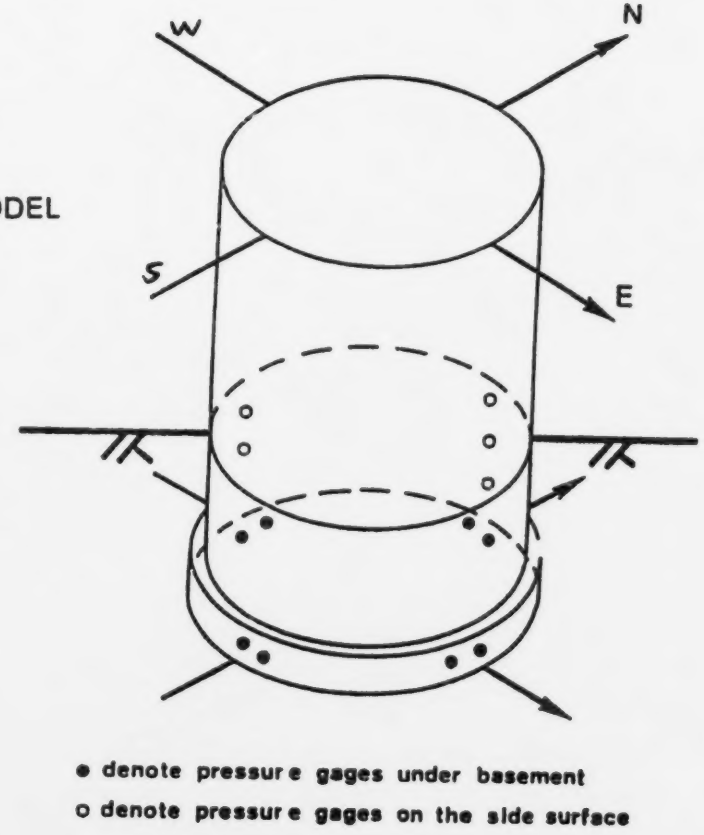

Figure 12 Interfacial Instrumentation.

from less than 2 km to over 80 km. Among them, the three most significant ones occurred on January 16, May 20, and July 30, 1986, with free-field peak ground accelerations recorded at 0.25 g, 0.2 g, and 0.18 g, respectively. Data reduction has indicated that a good earthquake data base has been obtained.

While the primary use of the records of the strong-motion event is in the validation exercise, the recorded structural response will also be used for the identification of modal parameters. The modal characteristics thus obtained will be compared with those derived from the vibration test response data to determine the change in the system during the earthquake.

SSI Methodology Validation Program

The methods selected for validation range from relatively simple lumped-parameter models to recently developed techniques involving detailed analytical/numerical treatment of the different aspects of the problem. The current program focuses on validating common practice in SSI analysis using existing methods. There will be no code/method development. Only the 1/4-scale model is covered in this program. While EPRI has selected different industrial practitioners to perform the tasks, NRC and the Argonne National Laboratory have sponsored a similar program in the universities, where many of the SSI analysis techniques originated. The methods selected include both the direct and the substructure techniques, while the site modeling may use finite-boundary or continuum approaches.

The plans for the validation program involve independent effort by each analyst to devise models, perform blind predictive calculations, and compare predictions with measurement leading to evaluation of the methodology. At least two models are to be constructed by each analyst in successive phases. In the earlier phase, the model(s) devised will be based only on information typically available in the nuclear plant design phase, i.e., soil boring and geophysical data. With such a model, the analyst will predict the response to dynamic excitation of the vibration tests if the methodology will permit such calculations. In the later phase, the model of the earlier phase may be modified, reflecting any additional knowledge gained from the vibration tests. The analysts will then use both the original and the modified models to predict both the site response and the structural response to a selected strong-motion seismic event, with only a measured free-field motion being given as input. Finally, the analyst will compare the predictions with measurements and document the results as well as descriptions of the approaches used and their justification.

4. APPLICATIONS

Seismic PRA methods have been used in recent years to clarify safety issues for nuclear power plants. The reason for this is the realization that seismic events can affect many plant systems simultaneously and, therefore, can be a significant or even dominant contributor to overall risk. The randomness of the seismic hazard, the uncertainties and variabilities of the needed data, and the approximate nature of the methodology raise questions

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of credibility of the results of seismic PRAs. At this stage in the development of seismic PRA methodology, we are not sure how "good" the results have to be to support a given regulatory action. But, one thing is certain: the use of probabilistic methods in licensing activities will continue to increase. For example, the Commission's 1985 Policy and Planning Guidance (NUREG-0885, Issue 4) includes the following planning guidance in its section on "Assuring the Safe Operation of Licensed Facilities":

12. Attention should be given to refining the use of probabilistic assessment techniques to implement Commission policy on safety goals, as directed by the Commission, and in other regulatory applications especially amenable to risk assessment, e.g., in dealing with generic safety issues, formulating new regulatory requirements, assessing and revalidating or eliminating existing regulatory requirements, evaluating new designs, and setting reactor research and inspection priorities.

13. Whenever probabilistic risk assessment is used in the decision-making process, there must be clear statements of the models used in the analysis with a clear identification of the most significant assumptions and a systematic evaluation of the most important uncertainties.

The most likely applications of the results of the research effort will be in:

1. Reassessment of the risk to the public associated with the possibility that earthquakes, larger than considered at the design stage, may occur at operating plants.

2. Assurance that the next generation of standardized plants, which are likely to use different seismic design approaches than the current generation, will meet the Commission's safety goals.

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Appendix F
Exchange of Seismic Research Information Project

NRC Project Manager: John J. Burns

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APPENDIX F

EXCHANGE OF SEISMIC RESEARCH INFORMATION PROJECT

1. INTRODUCTION

It is important that the NRC staff continually strive to improve its knowledge on the loading that can be induced in a nuclear power plant, on how the plant responds to that loading throughout its operational life, and finally on methods to ensure the safety of the public during the plant operation. This knowledge is gained through observing plant operations and through sponsoring research studies. However, the breadth of real and potential research needs related to loads, plant response, and plant safety is large. The research required to satisfy these needs will require a relatively large and continuous research budget. With a limited NRC research budget, it is desired to search out other sources of research information and projects that will assist in satisfying these research needs.

It is fortunate for the NRC that certain national and international organizations have and are conducting research whose results will be of value to the NRC in satisfying research needs. Similarly, such organizations could use the information and results gained from NRC-sponsored research. Agreements between the NRC and such organizations to exchange appropriate research results and plant operational information would be of benefit to the NRC. This could not only reduce the need for NRC research funds but provide the information at a more opportune time.

Discussions between representatives of the NRC and the Japanese Agency of Natural Resources and Energy (ANRE) have resulted in the opinion that there is an advantage to both sides, and appropriate utilities in both countries, for the exchange of seismic research and component fragility and equipment qualification information and data.

The purpose of this program is to develop an agreement between the NRC and ANRE for the exchange of specific packages of information and data related to seismic and other areas of research. It is anticipated that the exchange will result in experts who represent the NRC visiting with experts who represent ANRE to discuss in detail specific research projects. It is hoped that the information may result in cooperative and complementary research projects on each side.

2. BACKGROUND

In 1979, the NRC and ANRE began to explore the possibility of developing agreements for the exchange of research information available to each side. In 1982, in a joint meeting at the NRC, it was suggested that information be exchanged on the seismic response of nuclear power plants and soil-structure interaction during earthquakes. Further discussions led to a 1984 workshop on the exchange of seismic information. Here 25 specialists in seismic research

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from Japan met in Palo Alto, California, with 32 U.S. specialists representing the NRC, national laboratories, and the Electric Power Research Institute (EPRI) for 3 days to discuss available information for the exchange of various aspects of seismic research. At this workshop, an understanding was reached in regard to the mutual exchange of seismic research information.

At the 1984 workshop, the NRC suggested seven specific packages of exchange material related to seismic research. ANRE reviewed the suggested content in these seven packages and, in 1985, they suggested that the NRC consider only four of these packages.

During 1985 and 1986, negotiations continued on the development of exchange packages. On December 31, 1985, a Technical Exchange Agreement between the NRC, the Japanese Science and Technology Agency, and ANRE in the field of nuclear regulatory matters and nuclear safety research was signed. Also in August 1986, an agreement was signed between the NRC and ANRE to implement a cooperative seismic test of nuclear power piping at the Tadotsu Engineering Laboratory of the Nuclear Power Engineering Test Center (NUPEC).

The NRC and ANRE are currently discussing the possibility of conducting a second information exchange workshop in Japan in May 1988. The information exchange workshop topics to be discussed will be related to plant aging, materials engineering, nondestructive examination, and seismic response.

3. PROGRAM PLAN

At present, the NRC and ANRE are corresponding to establish an agreement to exchange four packages of seismic research information plus additional information packages related to containment integrity, plant aging, leak-before-break, and nondestructive examination. When the agreement is consummated, the Brookhaven National Laboratory will be funded to coordinate the exchange of information between the NRC and ANRE. Brookhaven has served for 5 years as the RES contractor in establishing relationships and assisting in the development of a general information exchange agreement between the NRC, ANRE, and the Japanese Science and Technology Agency. The program will contain four distinct tasks. First, in cooperation with ANRE, a detailed plan for the exchange of seismic information within each of the four exchange packages will be developed. Second, the detailed research information and data that the NRC wants from the ANRE files will be determined. This information will be requested from ANRE. The information received will then be assessed for its usefulness to the NRC. Similarly the information and data that ANRE desires from the NRC will be collected and transmitted to Japan. Third, if, after a review of the information and data received by the NRC, it is decided that personal visits by experts representing the NRC should be made to their counterparts in Japan, such visits will be arranged. The purpose of visits, from either side, will be to discuss further information needs, interpretation of the information received, and the potential for cooperative seismic research programs. Lastly, in conjunction with ANRE, plans for a Research Information Exchange Workshop, planned to take place in Japan in 1988, will be developed.

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The topics to be addressed at this workshop will involve not only those mentioned above, but also potential new topics established for potential exchange packages. The format of the workshop will be similar to the successful 1984 seismic information exchange workshop held in Palo Alto. It is anticipated that about 15 NRC contractor experts representing appropriate projects and five NRC representatives will attend the workshop, along with representatives from EPRI. It is intended that the NRC workshop representatives meet their project counterparts from Japan and discuss with them after the workshop the details of the exchange information. This may result in cooperative and complementary research between the NRC and Japan.

4. APPLICATION OF RESULTS

It is anticipated that the seismic research information and data received from ANRE will be complementary to the results of NRC-sponsored research in the same area and will therefore aid in satisfying existing seismic research needs. This information and data will be of similar interest to EPRI. Receiving appropriate information and data from Japan in this exchange program can save the NRC and EPRI large funds in the future that may have been spent to reproduce comparable data.

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Appendix G
Seismic Design Margins Program

NRC Project Manager: Dan Guzy

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APPENDIX G

SEISMIC DESIGN MARGINS PROGRAM

1. INTRODUCTION

The original plan (Ref. 1) for the Seismic Design Margins Program was published in October 1984 and later appeared as Appendix G of NUREG-1147. This has served as the basic outline for the research conducted to date in the RES projects entitled "Seismic Design Margins, LLNL FIN A0398," and "Trial Plant Review of Maine Yankee, LLNL FIN A0461." The majority of tasks in Phase I and Phase II of this plan have been completed, and this appendix will discuss briefly the status and products of these tasks. Proposed future tasks will also be discussed. However, it should be noted that the scope and schedule of these new tasks are now (May 1987) under development and subject to ongoing negotiations regarding possible NRC and Electric Power Research Institute (EPRI) cooperation in the seismic margins area and to future decisions about the role of the seismic margins approach in the implementation of the Severe Accident Policy Statement.

2. BACKGROUND

In 1984, the NRC Seismic Design Margins Program was initiated to provide the technical bases for better addressing seismic margins issues. The NRC Working Group of Seismic Design Margins was formed to help plan and oversee this effort. Special care was taken to consider potential licensing uses in developing the research plan. A panel of consultants was selected to provide expertise in the areas of seismic design, earthquake experience and testing, and seismic probabilistic risk assessments (PRAs). With support from the Lawrence Livermore National Laboratory (LLNL) and its subcontractors, this Expert Panel on the Quantification of Seismic Margins recommended a program plan (Ref. 1) that was endorsed by the NRC Working Group.

The Expert Panel also served as the chief innovator of a new approach for assessing the adequacy of nuclear power plant seismic margins (NUREG/CR-4334, Ref. 2). This approach has made use of the results and insights that have come from both the NRC-sponsored Seismic Safety Margins Research Program (Ref. 3) and from industry-sponsored seismic risk studies of the Zion, Indian Point 2, Indian Point 3, Millstone 3, Limerick, Seabrook, and Oconee nuclear plants. The seismic fragility (i.e., failure) information that was used in these studies (Refs. 4 and 5) has been reassessed in light of new dynamic test data for structures and equipment and recent systematic evaluations of earthquake experience in other heavy industrial facilities. The ongoing studies by the Seismic Qualification Utilities Group (SQUG) have been particularly useful in establishing lower bounds of fragility estimates for equipment. Current individual issues involving structure, equipment, and systems design were also factored into the recommended approach.

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The LLNL staff and its subcontractors worked with the Expert Panel to develop guidelines for seismic margins reviews (NUREG/CR-4482, Ref. 6) based on the panel's recommended approach. In 1986-1987, the major effort of the Seismic Design Margins Program has been the implementation of these guidelines in the trial seismic margins review of the Maine Yankee plant. While this review was a "trial" in the sense that it served to demonstrate the use of the new approach, the results of this review have been used to resolve an actual licensing issue for the Maine Yankee plant (Ref. 7). The Maine Yankee review was completed in March 1987 with the publication of the three volumes of NUREG/CR-4826 (Ref. 8).

3. PROGRAM OBJECTIVES

The current objectives of the Seismic Design Margins Program are:

1. To develop and improve guidance for assessing the inherent capabilities of nuclear power plants to withstand earthquakes above the design level.

2. To provide an effective and efficient means to identify vulnerabilities of nuclear plants to seismic events.

The first objective was the basis for the original program plan. It addresses issues such as the Charleston earthquake in which there may be future needs to evaluate the resistance of a plant to earthquakes larger than its Safe Shutdown Earthquake. The second objective reflects current planning for treatment of external events in the implementation of the Severe Accident Policy Statement. Current plans (Ref. 9) have included the Seismic Design Margins Program as part of the first phase of its external events program.

4. FY 1987 PROGRAM TASKS

4.1 Maine Yankee Seismic Margins Review

As mentioned in Section 2, the major recent effort of the Seismic Design Margins Program has been the trial review of the Maine Yankee plant. This effort has demonstrated the application of the guidance of NUREG/CR-4482 (Ref. 6) for a real case study that could serve as a benchmark for future seismic margins reviews. LLNL led an EQE Incorporated fragility analysis team and an Energy Incorporated systems analysis team in this review. Each organization prepared a volume of the final report (Ref. 8) that was reviewed by the NRC Seismic Design Margins Working Group. The Maine Yankee Peer Review Group (consisting of R. Budnitz, Chairman, M. Bohn, J. Reed, J. Thomas, and L. Wyllie) reviewed this study while in progress and provided an independent assessment of the final results.

The review was an 8-month, $500K effort that included two plant visits plus extensive data gathering and analyses. It should be noted that the Maine Yankee Atomic Power Company and the Yankee Atomic Electric Company contributed greatly to this effort through their transfer of information and overall cooperation.

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This review was completed in March 1987 as was the safety evaluation report on the Maine Yankee seismic issue (Ref. 7).

4.2 BWR Systems Study

Of the eight published seismic PRAs studied by the Expert Panel, all except the one for Limerick were for PWR plants. Because the PWR information base was more extensive, the systems review guidance given in NUREG/CR-4482 is more detailed for PWRs than for BWRs. (Note that components have greater similarities between plant type than do systems and thus the fragility review guidance pertains to both types of plant.) Since NUREG/CR-4482 was written, new BWR seismic PRAs became available for the LaSalle, Kuosheng, GE-SAR, Shoreham, and Susquehanna plants. These are now being studied in a task whose objectives are to provide BWR seismic margin systems guidance equivalent to that developed for PWRs in NUREG/CR-4482. The work is being done primarily by Paul Amico of the Applied Risk Technology Corp. and should be completed by the spring of 1987.

4.3 CDFM vs. PRA HCLPF Study

The seismic margins approach has chosen as its figure of merit a high confidence of low probability of failure (HCLPF). The HCLPF is a conservative representation of capacity and in simple terms corresponds to the earthquake level at which it is extremely unlikely that failure will occur. Two approaches are recommended in NUREG/CR-4482 for estimating component HCLPF values: the PRA fragilities approach and the Conservative Deterministic Failure Margins (CDFM) approach.

There is general acceptance of (and maybe a preference for) the CDFM concept; however, the NRC Seismic Design Margins Program has not yet provided a prescriptive procedure for this method. (Note that the Maine Yankee review uses primarily the PRA method.) The EPRI seismic margins program (discussed below), on the other hand, has chosen to further develop the CDFM method and is implementing this in the Catawba plant seismic margins review. EPRI's methodology includes a prescriptive set of CDFM calculational procedures that will serve as an NRC-sponsored benchmark in a study comparing results of the CDFM and PRA HCLPF methods. This will provide information about both the NRC and EPRI review guidance.

This task will be performed by LLNL and its subcontractors. It has been initiated and will be completed in the fall of 1987.

4.4 Expert Panel Activities

Although some members of the Expert Panel on the Quantification of Seismic Margins have been continually active in the program, the Expert Panel as a body has been essentially inactive since the publication of NUREG/CR-4482 and their endorsement of the initial Maine Yankee review procedures developed by

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the LLNL/EQE/EI review team. Assuming that the plan for EPRI/NRC cooperation is followed as outlined in Section 5, the Expert Panel would have one remaining task that would consist of an assessment of those items discussed in Sections 4.1-4.3.

This Expert Panel task is not seen as being a big effort and is included mainly for completeness. That is, as developers of the NRC seismic margins approach, they will have the opportunity to review their previous recommendations in light of the new information from the items discussed in Sections 4.1-4.3. While their assessments will be documented, no formal revision of NUREG/CR-4482 is planned at this time.

5. EPRI SEISMIC MARGINS PROGRAM

A separate EPRI seismic margins program is currently under way. This program has the same broad objectives as the NRC program, and much of its methodology has evolved from the concept and approaches developed by the Expert Panel on the Qualification of Seismic Margins. However, while the NRC guidelines and procedures are tailored toward use by a review team comprised of members from consulting firms, architect-engineering firms, and/or DOE laboratories, the potential users of the EPRI procedures are the utilities themselves. EPRI is attempting to provide procedures that are simpler, more prescriptive, and more tractable than the NRC procedures. Toward this goal, EPRI has chosen to endorse the CDFM HCLPF method (discussed in Section 4) and has taken a systems "success path" approach. Following the success path approach, it is only necessary for the system engineers to define those components required for an operational sequence of plant systems that will bring the plant to a stable condition (either hot or cold shutdown) and maintain that condition for at least 72 hours. Several possible success paths exist. The idea is to select the success path for which it will be easiest to demonstrate an adequate seismic margin.

The EPRI methodology report (Ref. 10) is in draft form. It addresses BWR systems as well as PWR systems and also provides more detail on the treatment of soil-structure interaction and soil failure than does NUREG/CR-4482.

Currently, EPRI is funding a margins review of the Catawba plant using this methodology. The Catawba study should be finished in the spring of 1987.

6. FUTURE NRC AND EPRI COOPERATION

It should be noted that there has been a good exchange of information between the NRC and EPRI seismic margins programs. The NRC and EPRI held a workshop on seismic margins in October 1984. The NRC-sponsored Maine Yankee review team has met twice with the EPRI-sponsored Catawba review team to discuss walkdown techniques and experiences. Presentations from both research programs have been made before SQUG and ASCE committees and at conferences.

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Negotiations are currently under way to establish greater cooperation between the EPRI and NRC programs. The goals for this cooperation are to pool resources and to provide active industry and NRC participation in the development of a seismic margins review procedure that can later be used to address licensing issues. This merger of the now separate NRC and EPRI research programs is intended to result in the joint acceptance of seismic margins review guidelines that will be demonstrated in a trial BWR plant review. An obvious advantage of combining efforts in the developmental stage is that it prevents the divergence of evaluation philosophies that may only be resolved later in the licensing arena. (The NRC/SQUG involvement in Unresolved Safety Issue A-46 is a good example of successful industry/NRC cooperation.)

The first steps toward NRC and EPRI cooperation are under way. A thorough NRC review of both the EPRI methodology and Catawba study reports has begun. A new, independent consultant review panel has been formed to review this material and will report their findings and recommendations to the NRC Seismic Design Margins Working Group in June 1987. The EPRI methodology would either be endorsed outright or suggested revisions would be offered by the NRC. Assuming that any differences are easily reconciled, the cooperative effort would next proceed with a trial BWR seismic margins review. EPRI would establish utility cooperation (with NRC concurrence on plant selection) and would contract and manage the review itself. The NRC would establish and fund a peer review group (similar to the one for the Maine Yankee study) that would provide an independent assessment. Upon completion of the BWR study, the review procedures would be reassessed in light of the lessons learned. Unless open items are identified, this would essentially complete the cooperative EPRI/NRC program.

The proposed outline for EPRI/NRC seismic margins cooperative research is currently only in the initial planning stage. A rough schedule estimate of this would have the NRC review of the EPRI reports completed in June 1987 and the BWR review initiated in the summer of 1987. The review should be completed in 1988.

Beginning in 1987, work to modify and implement the existing seismic margins procedures for use in implementing the Severe Accident Policy Statement will be performed.

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*Available in the NRC Public Document Room, 1717 H Street NW., Washington, DC.

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This document presents a plan for seismic research to be performed by the Structural and Seismic Engineering Branch in the Office of Nuclear Regulatory Research. The plan describes the regulatory needs and related research necessary to address the following issues: uncertainties in seismic hazard, earthquakes larger than the design basis, seismic vulnerabilities, shifts in building frequency, piping design, and the adequacy of current criteria and methods. In addition to presenting current and proposed research within the NRC, the plan discusses research sponsored by other domestic and foreign sources.

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